

# Chapter 1

## Introduction

Nature manifests it self in two forms, radiation and matter. The interaction between these two bears an importance as deep and wide as nature it self. The complete range of radiations extending from gamma radiations, with extremely small wave lengths, to radio waves, with very high wave lengths, is called the electromagnetic spectrum. The classical electromagnetic theory predicted, continuous transmission of radiation from one spatial point to another. But the *Quantum Theory of Radiation*, proposed by Max Planck which proved beyond doubt, the discrete nature of radiation dealt a fatal blow to this theory. According to the quantum theory, each quantum, called a *photon* — carries an energy  $E = h\nu$  where  $h$  is the planck's constant and  $\nu$  the frequency of radiation. It is interesting to note that eventhough each photon is characterized by a definite quantity of energy, the basis of classification is its mode of origin. Those photons having their origin in the atomic nucleus are called *gamma rays*. Photons produced as a result of acceleration of charged particles are called *Bremsstrahlung* or *continuous X - rays*, and those emitted during transition of orbital electrons are called *Characteristic X - rays*. The photons produced during *positron - electron annihilation* are called *annihilation radiation*. The energies of gamma radiations cover several orders of magnitude of the entire

electromagnetic spectrum.

The interaction of radiation with matter is independent of its origin but depends on its energy. The diverse phenomena associated with the above interaction makes it highly complex. Each process involved in it possesses its own individual distinctive characteristics. The nature of the medium with which the gamma ray interacts presents a wide range of phenomena as does the nature of the gamma ray. *The current work deals with the interaction of gamma radiation with matter within the range of energy 30 - 1500 keV, which is found to be the most useful in medical, biological and industrial applications.*

In the study of gamma ray interaction with matter, the overall behaviour of an absorber or scatterer may be derived by considering it as a collection of individual atoms. Each atom interacts with the incident photon independently. The surrounding environment of the atom have nothing to do with the nature of interaction. Invariably such processes are single and identifiable. Each of these processes is associated with an individual atom and hence may be characterized by what is called, a *cross section*, which is a measure of the probability of interaction.

The process involved during interaction of an atom with a gamma ray photon, as explained above, may be principally a scattering event in which no energy is imparted (*coherent scattering*) or part of the energy is imparted (*incoherent scattering*) to the atom concerned or to any of the orbital electrons in it. It may be essentially an absorption process in which the entire energy of the photon is transferred to the interacting atom (*photoeffect*). In such cases where energy of the incident gamma ray photon exceeds a threshold of 1.02 MeV, materialization of energy may take place (*pair production*) in the vicinity of the nucleus of the atom with which the photon interacts.

Whichever be the process involved in the interaction of the primary

beam of gamma rays with the absorber or scatterer through which it passes, the interacting photons will be removed from the primary beam in a single event (provided the beam is well collimated). Therefore the total attenuation of the transmitted beam is a measure of the interaction that took place in the absorber.

If we consider a well collimated narrow beam of gamma rays passing through a homogeneous sample of thickness  $x$ , the ratio of the intensity of emerging beam from the target along the incident direction, to the incident intensity is given by the Beer Lambert law

$$\frac{I}{I_0} = \exp -\mu x \quad (1.1)$$

Where  $\mu$  is the linear attenuation coefficient of the sample target.  $\mu/\rho$  is called the total mass attenuation coefficient of the sample whose density is  $\rho$ . It is related with the atomic weight of the target by the relation

$$\frac{\mu}{\rho} = \frac{N_A \sigma_{total}}{A} \quad (1.2)$$

where  $N_A$  is the Avogadro constant and  $\sigma_{total}$  the total attenuation cross section per atom or molecule of the target.

In the energy region 30 - 1500 keV, for low  $Z$  elements, the contribution of pair production to the total attenuation cross section is very small and hence be neglected. Thus we can write

$$\sigma_{total} = \sigma_{total}^{ph} + \sigma_{total}^{coh} + \sigma_{total}^{incoh} \quad (1.3)$$

where the 1st, 2nd and 3rd terms in the RHS represent the contribution to *atatai* from photoeffect, coherent scattering and incoherent scattering respectively.

*The mixture rule* [Deslattes (1969)] provides a very convenient and effective way to calculate the mass attenuation coefficient of a chemical compound or homogeneous mixture from the weighted sum of the coeffi-

coefficients for the constituent elements. Hence

$$\frac{\mu}{\rho} = \sum_i w_i \left( \frac{\mu}{\rho} \right)_i \quad (1.4)$$

where  $\left( \frac{\mu}{\rho} \right)_i$  is the mass attenuation coefficient of the  $i^{\text{th}}$  element and  $w_i$  its proportion by weight

Any change in the atomic wave functions as a result of the molecular, chemical and crystalline environment are neglected in the mixture rule. The errors are expected to be generally less than a few percent for photon energies above 10 keV and less than 2% at energy 1 keV or more away from an absorption edge (error is discussed in more detail in Chapter V). Near the absorption edge there may be considerable fine structure which varies with the chemical composition and the state of aggregation.

## 1.1 A survey of theoretical studies on total attenuation coefficients

Davisson and Evans (1951,1952) have reviewed both the theoretical and experimental works till 1952 and compiled earlier attenuation coefficient measurements.

Grodstein (1957) and Davisson (1955) separately reviewed and compared the theoretical and experimental works.

Hubbell (1969) tabulated attenuation coefficients for 23 elements ( $Z = 1$  to 92) between 10 keV and 100 GeV and for air, water and 7 elements up to 100 MeV. It contains detailed information on the individual predominant processes of interactions, and their cross sections between 10 keV and 100 GeV for 23 elements and for 13 compounds and mixtures.

Storm and Israel (1970) have tabulated attenuation and energy absorption coefficients of all elements from  $Z = 1$  to 100 for photon energies in the range 1 keV to 100 MeV.

Biggs and Lighthill (1971) have provided a compact parametrization of attenuation coefficient data extending down to 0.01 keV. They have derived empirical formulae, for the attenuation coefficients of mixtures by fitting data with sums of polynomial or exponential functions. By the very nature of their empirical formulae, they are valid only over the fitted range of  $Z$  and  $E$ . They offer no new insight into the Physical processes involved and do not lead to an effective atomic number or to any other parameter of the mixture rule.

Hubbell (1971) has provided a bibliography of 290 references containing absolute-value photon total cross section data above 10 eV, covering the period 1909 to 1971 for  $Z = 1$  to 94. Graphs are presented for 17 elements ( $Z = 10$  to 92) over the energy range 100 eV to 10 MeV comparing some attenuation coefficient tabulations by the Lawrence (Livermore) Radiation Laboratory, National Bureau of standards, Los Alamos Scientific Laboratory, and others, with the above documented data points.

Simmons and Hubbell (1973) used Biggs-Lighthill (1971) parameters and formulae to compute an explicit tabulation of data set, synthesized from available compilations. The above compilations are of attenuation and energy absorption coefficients for pure elements, with few minor exceptions.

Veigele (1973) compiled experimental photon attenuation cross sections for elements H to Pu for energies in the range 0.1 keV to 1 MeV, from literature available to the end of 1970. Scattering cross sections calculated by relativistic self-consistent-field methods, were subtracted from total attenuation data, and the resulting photoeffect and measured photoeffect cross sections from 1 keV to 1 MeV were fitted by a least squares procedure. The theoretical scattering cross sections were then added to the resulting values to obtain total attenuation coefficients. From 0.1 keV to between 1 keV and 10 keV, non-relativistic, self-consistent-field, independent-electron theory was used to calculate photoeffect cross sections. Theoretical scat-

tering values were added to obtain total attenuation cross sections. Uncertainties were estimated.

Hubbell (1974) has reviewed the developments in theoretical and experimental cross sections for the basic photon interactions — photoeffect, coherent and incoherent scattering and electron-positron pair production — with emphasis given to the extensive total and sub shell photoeffect calculation by Scofield (1973) and atomic form factor and incoherent scattering function data calculated by Cromer and Mann (1967,1968, 1969) and Brown (1970, 1971, 1972, 1974). Some comparisons of these theoretical results with available explicit cross sections and total attenuation coefficient measurements are presented. The results are presented graphically.

Kim (1974) and White & Fitzgerald (1977) have computed attenuation and energy absorption coefficients for human organs and tissues using average chemical compositions.

Cho et al. (1975), McCullong (1975) and Rutherford et al. (1976) applied the equation for total attenuation coefficient of a single element, which is a function of atomic number  $Z$ , photon energy  $E$  and electron density  $nZ$  (where  $n$  is the number of atoms per unit volume), in which functions of  $Z$  and  $E$  have been obtained by fitting data at several energies to complex materials. It has led to various definitions of effective atomic number and effective electron density.

Hubbell (1976) compared the mass attenuation coefficients  $\mu/\rho$  developed at the National Bureau of Standards by the X-ray and Ionizing Radiation Data Center from the latest theoretical cross section data with measurements for selected low  $Z$  elements of dosimetric interest. From this cross section data base, mass energy absorption coefficients  $\mu_{\text{en}}/\rho$  were derived for air and selected media, along with air/medium ratios, over the photon energy range 0.1 keV to 20 MeV including values at the  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  energies. Comparisons were made with previously published  $\mu_{\text{en}}/\rho$

values and air/medium ratios. Results were tabulated.

Hubbell and Veigele (1976) used experimental values of total attenuation cross sections, available in the literature, to derive photoeffect cross sections in the energy range 0.1 keV to 1.5 MeV. The results both calculated and experimental, were presented graphically as a function of photon energy for all elements from  $Z = 1$  to 94. The calculated results presented are (1) the non-relativistic Hartree-Fock self-consistent-field (SCF) results of Veigele, Henry et al. over the range 0.1 keV to between 1 and 8 keV for all elements  $Z = 1$  to 94 and (2) the relativistic Hartree-Slater SCF results of Scofield over the range 1 keV to 1.5 MeV for all elements  $Z = 1$  to 101.

Kourios et al. (1978) have examined the feasibility of elemental analysis based on detection of differences in attenuation coefficients, for composite materials and this method has been applied to the detection of various elements in a wood matrix by Tout et al. (1977).

Plechaty et al. (1978) made tabulation of attenuation and energy absorption coefficients similar to that of Storm and Israel (1970) but extending the energy down to 0.1 keV. They have combined the tabulations of McMaster et al. (1969), Veigele et al. (1971) and other data sources.

Jackson and Hawkes (1981) have reviewed mass attenuation coefficients for pure elements and mixtures. They derived parametrizations for individual processes of interaction and thus derived an accurate parametrization for the atomic total attenuation cross sections.

$${}_a\sigma(Z, E) \simeq {}_a\sigma_{1s}^{ST}(Z, E) \sum_n \left\{ (\sigma_{ns}^{ST} / {}_a\sigma_{1s}^{ST})^{lim} \check{N}_{ns}(Z) [1 + F_{ns}(\beta)] \right\} + Z_e \sigma^{KN}(E) + (1 - Z^{b-1})(Z/Z')^2 {}_a\sigma^{coh}(Z', E') \quad (1.5)$$

where  ${}_a\sigma(Z, E)$  is the atomic total attenuation cross section for the element with atomic number  $Z$  at the energy  $E$ ,  ${}_a\sigma_{1s}^{ST}$  Stobe(1930) photo effect cross section for 1s state,  $\check{N}_{ns} = (N_{ns}/N_{ns}^c)^2$ , ( $N_{ns}$  and  $N_{ns}^c$ , are the normalization coefficients which give the screening correction to the Stobe cross

section due to the change in normalization of the bound-state wave functions.  $\beta = v/c$  ( $v$  is the relativistic velocity of electron and  $c$  is the velocity of light in vacuum),  ${}_e\sigma^{\text{KN}}(E)$  Klein Nishina or free electron cross section at energy  $E$ ,  $F_{\text{ns}}(\beta)$  the empirical relativistic cross section for the atomic photo effect cross section; denned by  $1 + F_{\text{ns}}(\beta) = 1 + 0.143\beta^2 + 1.667\beta^8$ ,  $Z'$  atomic number of a chosen standard element,  $b = 0.5$  for the range of elements encountered in tissues,  $E' = (Z'/Z)^{1/3}E$ ,  $\sum_n ({}_a\sigma_{\text{ns}}^{\text{ST}} / {}_a\sigma_{1s}^{\text{ST}})^{\text{lim}}$ ,  $\check{N}_{\text{ns}}(Z) = \sum_n n^{-3}\check{N}_{\text{ns}}(Z)$  is a function of  $Z$  only. This function is obtained from Scofield's tabulation of the normalization coefficients with the HS (Herman and Skillman) potential. The quantity  $1 + F_{\text{ns}}(\beta)$  is the same for all  $n$ . Therefore the quantity

$$UN(Z, E) = \frac{{}_a\sigma^{\text{ph}}(Z, E)}{\{{}_a\sigma_{1s}^{\text{ST}}(Z, E)[1 + F_{\text{ns}}(\beta)]\}}$$

is independent of  $n$ . Examination of this quantity showed that the energy variation is less than 1% for  $E$  between 30 to 150 keV even for elements with high  $Z$  where the 2p contribution to the photoelectric cross section is significant. This result is in agreement with that of Pratt et al. (1973) that  ${}_a\sigma^{\text{ph}} / {}_a\sigma_{1s}^{\text{ph}}$  is to good approximation, independent of energy. Using this result, optimised energy-independent coefficients  $UN(Z)$  which are averaged values for each value of  $Z$  for the energy range 30 to 150 keV have been obtained. Equation for  ${}_a\sigma(Z, E)$  given above gave very good results over a very wide energy range, with a discrepancy at high  $Z$ . This discrepancy is removed by using the optimised function  $UN(Z)$  except at high energy. Since the contribution of  ${}_a\sigma^{\text{coh}}$  and  $\sigma^{\text{ph}}$  to the total is relatively small at high energies, the results at high energies remain good.

They have used the accurate parametrization to determine the physical parameters of a complex medium, such as electron density in the mixture in comparison with that in the standard element, difference between mean atomic number and the atomic number of the standard element etc. It also yields information regarding changes in the physical characteristics of the

medium, such as density or state of aggregation or physical changes arising from changes in chemical composition or structure etc.

They conclude that definition of one or two effective atomic numbers characterizing a mixture, such as tissue, is not valid over wide energy ranges or for mixtures containing elements of much different atomic number, although it does provide a very useful approximation for a variety of radiation studies and does lead to consistent results in certain cases. Of greater importance is the conclusion, that neglect of the coherent cross section, which leads to the definition of a single effective atomic number, is extremely suspect in the energy region relevant to diagnostic X-rays and is not satisfactory for accurate work with mixtures containing elements of low atomic number, such as biological tissue. Even when the cross sections of all elements are assumed to have the same energy dependence only given by  $\sigma^{\text{KN}}$  and  $F(E)$ , there are still significant discrepancies over wide ranges of  $Z$  and  $E$ .

Hubbell (1982) has provided a very useful and extensive tabulation of mass attenuation coefficients and mass energy-absorption coefficients for 40 elements ranging from Hydrogen ( $Z = 1$ ) to Uranium ( $Z = 92$ ) for photon energy in the range 1 keV to 20 MeV.  $\mu/\rho$   $\mu_{\text{en}}/\rho$  values for 45 mixtures and compounds of dosimetric interest in the same energy range are also given. The data given for pure elements have been used to derive the corresponding data for the mixtures and compounds. This work is mainly based on theoretical data. Scofield (1973) computations have been used with minor empirical modifications, for the atomic photoeffect cross sections. The tabulations of Hubbell et al. (1977,1979) are used for incoherent (non-relativistic) and coherent (relativistic) scattering cross sections. It also includes the pair and triplet cross sections calculated by Hubbell et al. (1980) using atomic form factor and incoherent scattering function data given in Hubbell et al. (1977) and Hubbell et al. (1979). Differences from

Hubbell, NSRDS - NBS 29 (1969) and Storm - Israel (1970) are of the order of 1% or less over most of the element-energy range, but in some cases are as much as 5%.

A computerized photon attenuation data base has been developed by NBS Photon and Charged Particle Data Center for the photon energy range 10 eV to 100 GeV and for elements, with  $Z = 1$  to 94. Henry, Gerstenberg and Hubbell (1983) have presented an example for using this data base in the critical evaluation of a theory-based data-set. The data-base permits easier statistical analysis of the measured  $\mu/\rho$  values, as well as a variety of computer-graphics aids to critical evaluation of the best set theoretical or quasi-theoretical compiled  $\mu/\rho$  data.

Hubbell et al. (1986) have presented a bibliography of papers reporting absolute measurements of photon total interaction cross sections or attenuation coefficients for elements and some compounds. It covers, an energy range 10 eV to 10 GeV and the period from 1907 to 1986. The bibliography includes about 500 nonduplicative references to a total of about 20,000 data points, available in machine readable form.

Saloman and Hubbell (1986) have presented for the energy range 0.1 to 100 keV the National Bureau of Standards data base of experimental X-ray attenuation coefficients and cross sections calculated using a relativistic Hartree-Slater model for the photoeffect cross sections for all elements of atomic number  $Z = 1$  to 92. The information is displayed in both tabular and graphical form. The cross sections obtained using the semiempirical set of recommended values of B. L. Henke and co-workers are also shown graphically.

Berger and Hubbell (1987) have developed a computer program XC-OM, and data base, which can be used to calculate, with a personal computer, photon cross sections for scattering, photoeffect and pair production, as well as total attenuation coefficients, in any element, compound or mix-

ture, at energies from 1 keV to 100 GeV. It is based on the conclusions developed from comparisons with measurements via the Saloman, Hubbell and Scofield work (1988) and uses the unrenormalized Scofield photoeffect values.

Saloman et al. (1988) and Manson (1989) have reviewed the existing experimental data situation for X-ray attenuation coefficients of the elements in the energy range from 0.1 to 100 keV,

Gerward (1992) has presented the current state of knowledge of X-ray attenuation coefficients in the photon energy range 1 to 100 keV which includes several new sources of experimental and theoretical data, compilations, tables and other useful tools for calculation of X-ray attenuation in matter.

The International Union of Crystallography (IUCr) has started a project aimed at improving the techniques for the measurements of attenuation coefficients and for producing better sets of tables for experimenters, and following it some papers have been published (Creagh and Hubbell, 1987, 1990, 1992).

## **1.2 Survey of experimental work on photon attenuation cross section**

A fairly large number of experimental works have been carried out on elements, certain mixtures, compounds and alloys in good geometry setup producing satisfactory agreement of experimental results with corresponding theoretical results.

Wiedenbeck (1962) has measured total attenuation coefficients for Be, C, Al, Fe, Co, Ni, Cu, Nb, Mo, Ag, Cd, In, Sn, Ta, W, Pt, Au, Pb, and Th; for different energies in the range 39.52 to 412 keV. The DuMond bend-crystal spectrometer was used for the analysis of the scattered radiation.

The photons so analyzed were detected by a 3 inch NaI(Tl) crystal with an energy resolution of 12%. The influence of the position of the absorber from the source was investigated and found that the measured counting rate of the transmitted radiation was independent of the absorber position. The results obtained were in general agreement with earlier tabulation at energies above the K-edge, but are higher than most estimates at energies below the K-edge.

McCrary et al. (1967) have measured total attenuation coefficients of Be, C, Mg, Al, S, Ti, Fe, Ni, Cu, Zn, Zr, Nb, Mo, Ag, Sn, La, Gd, Hf, W, Au, Pb, Th, U and Pu in a narrow beam geometry with a Bragg diffraction monochromator, in the energy range 24 to 131 keV. The results obtained are in good agreement with the results of Deslattes (1958) and Bearden (1966) in the energy region 25 to 30 keV.

Grimvall and Persson (1969) made use of an X-ray double-crystal spectrometer, which has been described by Brogren (1951), for the measurement of absorption coefficient of germanium for energies 5.415 to 41.33 keV. From the experimentally obtained absorption coefficients, they have calculated the oscillator strength for the K-electrons for the photoeffect absorption. There is good agreement between experimental and theoretical values.

Parthasaradhi et al. (1969) have measured total attenuation cross sections of Pb, Pt and Sn for 280 keV photons, using a narrow beam geometry developed by Lakshminarayana (1960) and Lakshminarayana & Jnanananda (1961).

McCrary et al. (1970) have measured mass attenuation coefficients of Air, Neon, Argon, Krypton and Xenon in the energy range 4.508 to 145.43 keV, in a narrow beam geometry. The theoretical values of  $\mu/\rho$  for the samples used, at the energies of interest were calculated by the relation

$$(\mu/\rho)_t = (\mu/\rho)_r + (\mu/\rho)_i + (\mu/\rho)_c$$

where  $(\mu/\rho)_t$  is the total attenuation cross section in  $\text{cm}^2/\text{g}$ .  $(\mu/\rho)_r$ ,  $(\mu/\rho)_i$  and  $(\mu/\rho)_c$  are the photoeffect cross section, the total incoherent cross section for bound electrons and the coherent scattering cross section respectively. The photoeffect cross sections were computed by a modified version of the Brysk and Zerby (1968) method which uses bound-state wave functions and potentials from a relativistic Dirac-Slater self-consistent field programme of Liberman et al. (1965). McCrary et al. used an improved treatment of the Slater exchange term. So the wave functions used were slightly different from those of Liberman et al. (1967). Unlike the Brysk and Zerby method the experimentally determined values of electron binding energies given by Bearden (1967) were used here. The photoeffect cross sections have been calculated by the method given in Rakavy and Ron (1967) and Brysk and Zerby (1967).

The total incoherent cross section for bound electrons was calculated using the Klein-Nishina equation. The incoherent scattering functions computed with Hartree-Fock wave functions using all exchange terms by Cromer and Mann (1967) were used for spherically symmetric free atoms and by Cromer (1969) were used for the aspherical free atoms. The coherent scattering cross section was calculated from

$$d(\mu/\rho)_c/d\Omega = \frac{1}{2} r_0^2 (1+\cos^2\theta)F^2(q,z)$$

by numerical integration over the scattering angle  $\theta$ . Here  $F(q,z)$  is the form factor which gives the probability that the recoil momentum  $\vec{q}$  is transferred to the  $Z$  electrons with no energy absorption. There is a good agreement between experimental and theoretical values.

Gopal and Sanjeevaiah (1973<sub>a</sub>) have studied the percentage resolution of the scintillation spectrometer, by interposing absorbers, (C, Al, Cu, Sn and Pb) with different thickness. They employed the counting sequence of Conner et al. (1970) to obtain the gamma ray attenuation coefficients at 661.6 keV, using an experimental arrangement similar to that of Davisson

and Evans (1951) with little modifications. The angle of acceptance was 16 minutes. They observed an increase in percentage resolution and total attenuation cross sections with increase in  $\mu t$  above 1. With increase in  $\mu t$  above unity, the lower energy side of the photopeak was found to broaden which increased with  $\mu t$ . The effects are shown graphically for elements of lowest and highest  $Z$  used. The changes are attributed to the increase in multiple scattering effects with the increase in attenuator thickness. However the multiple scattering effect is found to be negligible when  $\mu t < 1$ . They carried out the investigation for values of  $\mu t$  up to 4.2.

Gopal and Sanjeevaiah (1973<sub>b</sub>) once again established the dependence of absorber thickness on the percentage resolution of the detector, and the total attenuation coefficient of the absorber for 84 keV gamma rays. The effects are reported graphically. The broadening of the lower energy side of the photopeak also is shown graphically. They have concluded that the accuracy in the measurement of total attenuation coefficient may be increased to a great extent by using the criterion  $\mu t < 1$  and the counting sequence of Conner et al. (1970) which will effectively reduce the effect of multiple scattering to a minimum. Adopting this method they have measured total attenuation coefficients of carbon, aluminum, copper, tin and lead at gamma energies 84 to 411.8 keV. The results are in general agreement with the values of Conner et al. (1970) except at certain cases, where disparities could be observed. The disparity is attributed to the fact that Conner et al. did not choose the criterion  $\mu t < 1$  in all the cases. In certain cases  $\mu t$  has gone up to 2.3 in their measurements.

Goswami and Chaudhuri (1973) made an accurate measurement of gamma ray attenuation coefficients using a highly collimated narrow beam transmission method which effectively excluded corrections due to small-angle and multiple scattering of photons. Attenuation coefficients have been reported for 34 elements with  $Z = 1$  to 82 in the energy range 662 to 1332

keV. The angle of acceptance for the scattered photons was 24 minutes. A 2.5 cm NaI(Tl) crystal detector was employed for the study. For elements which are not available in the foil, powder or liquid forms, their compounds (in the form of powder) have been used. They derived the attenuation cross sections of Hydrogen from the measured attenuation cross sections of some hydrocarbons in the liquid form, applying the mixture rule. The total attenuation cross sections of some elements obtained experimentally are in satisfactory agreement with the corresponding values of Conner et al. (1970), Colgate (1952), Davisson and Evans (1952).

Parthasaradhi and Hanson (1974) reported total photon attenuation cross sections at a series of energies from 3.3 to 165.8 keV for the elements Al, V; Cu, Mo, Sn, Ta, Au, and Pb. They have used Ge(Li) and Si(Li) detectors in a good geometry setup in their study. A 5% deviation is observed with the results obtained. The photoeffect cross sections have been derived by the subtraction method and the authors claim an accuracy within 3%, for the results obtained.

In this laboratory, Ramakrishna Gowda and Sanjeevaiah (1974) used a NaI(Tl) crystal detector in a narrow beam geometry setup and measured the total attenuation coefficients of Al, Cu, Zr, Ag, Sn, Ta, Au and Pb for 72.1 keV photons of  $\text{Hg}^{203}$ . They followed the counting sequence of McCrary et al. (1967) along with the condition,  $\mu t < 1$  (Gopal and Sanjeevaiah, 1973), for minimizing multiple scattering effects. Except for Au and Pb the experimental values are in agreement with the interpolated values of McCrary et al. The photoeffect cross sections were derived from the measured total attenuation cross sections by subtracting the theoretical values of scattering contributions.

Ramakrishna Gowda et al. (1976) measured the total attenuation cross sections of Al, Cu, Zr, Ag, Sn, Ta, Au and Pb for 52.2 and 84.3 keV photons in the same experimental setup used by Ramakrishna Gowda

and Sanjeevaiah (1974). Photoeffect cross sections were obtained from the experimental values of total attenuation cross sections by the subtraction method. The results were compared with those available in the literature,

Ramakrishna Gowda et al. (1976) have measured total attenuation cross sections of Al, Cu, Zr, Ag, Sn, Ta, Au and Pb at energies 32.2, 52.2 and 84.3 keV, employing a NaI(Tl) detector in a good geometry setup. The photoeffect cross sections are derived from the measured cross sections by the subtraction method.

Reddy et al. (1976) obtained total attenuation cross sections of U, Th, Pb, and Au at energies 30.9, 35.9 and 55.4 keV. They used a Krypton-filled proportional counter for the detection of transmitted photons. In this case they modified the narrow beam setup so as to have more angle of acceptance for scattered photons, to compensate for the low efficiency of the proportional counter and applied corrections for small angle coherent and incoherent contributions. The total attenuation cross sections obtained were compared with the values of McCrary et al. (1967), Perkin & Douglas (1967) and Wiedenbeck (1962), and deviations reported. Photoelectric cross sections for the samples used are derived from the measured total attenuation cross sections by the subtraction method.

Canada et al. (1977) have measured the mass attenuation coefficients of Plutonium for various energies between 96.7 to 199 keV. There is an average deviation of 4% between the measured values of attenuation coefficients and the values of Veigele (1973), below the edge. However the deviation above the edge is less than 1%. They obtained the K-absorption edge value of plutonium to be  $(121.795 \pm 0.014)$  keV.

Kane et al. (1977) used a good resolution Ge(Li) detector in a narrow beam geometry and measured attenuation coefficients of lead, tantalum and molybdenum in the energy range 662 to 1330 keV. They studied the multiple scattering effects on the dependence of the percentage resolution,

gamma ray attenuation coefficients and broadening of the lower energy side of the photopeak on the attenuator thickness, reported by Gopal et al. 1973, and found to be small up to the corresponding *mean free path* of the gamma ray. The results obtained are in good agreement with the interpolated theoretical values except in the case of Molybdenum.

Rajendra Prasad (1978,1980) studied the total attenuation cross sections of elements Al, Fe, Mo, Ag, W, Pt, Ca, V, Ni, Zn, Y, Cd, In and Nd for various values of energy below 100 keV. 4% deviation is recorded by comparing the results obtained with the available theoretical values. The photoeffect cross sections of the elements are obtained from the experimental total attenuation cross sections by the subtraction method.

Berry and Lawrence (1979) reported X-ray attenuation coefficients of graphite for energies up to 31.07 keV, using the method adopted by Lawrence and Mathieson (1976). The international Tables for X-ray Crystallography (1974) from which they have obtained theoretical values for comparison of experimental values, contains full contributions from Bragg scattering. The experimental values are slightly higher due to the Bragg scattering.

Lawrence (1979) used polycrystalline samples of magnesium and aluminum to measure mass attenuation coefficients in the energy range 9.68 to 40.52 keV. He has estimated the contributions of Bragg, thermal diffuse, Compton scattering and derived the photoeffect coefficients, for the two elements. The dependence of mass absorption coefficients on wave length has been studied and found to be the same for the polycrystalline samples of both the elements. An excellent agreement is reported between the experimental values and the values of Miller and Greening (1974). However their results are higher by 2% from the values of International Tables for X-ray Crystallography (1974).

Puttaswamy et al. (1979) measured total attenuation cross sections

of the elements C, Al, S, Cu, Zr, Ag, Sn, Ta, Au and Pb for photon energies 5, 5.9, 6.4, 8.1, 10.6, 14.4, 24.7, 32.9, 36.9, 66.6 and 129 keV. A proportional counter filled with Krypton gas and a thin NaI(Tl) detector, were used in the measurement, in the energy ranges 5 to 25 keV and 30 to 130 keV respectively. The total attenuation cross sections obtained are compared with other experimental values available in the literature. In most of the cases there values were higher particularly at energies 32 and 36.9 keV. An improvement in agreement was observed with increase in  $Z$  and energy. Photoeffect cross sections were derived by subtracting the theoretical scattering contributions from the measured total attenuation cross sections. The values so obtained were in good agreement with the corresponding values of Scofield (1973).

Ramakrishna Gowda et al. (1979) noticed a trend of decrease in error in the total attenuation cross section measurements of several elements like C, by many investigators. In view of the fact, that the convergence of the measured values was to be determined, they measured total attenuation cross sections of C, with radio active sources which emit K X-rays as sources at energies 5, 5.9, 6.4, 8.1, 10.6 and 14.4 keV, using a Krypton filled proportional counter, in a good geometry setup. The values so obtained were compared and discussed with values available in the literature.

Puttaswamy et al. (1981n) measured total attenuation cross sections of Al, S, Cu, Zr, Ag, Sn, Ta, Au, and Pb at 31.7, 74.8, 81 and 145 keV and derived photoeffect cross sections of these elements by the subtraction method. The photoeffect cross sections so obtained were in good agreement with the corresponding values of Scofield (1973).

Puttaswamy et al. (1981<sub>b</sub>) extracted total attenuation cross sections, total and K-shell photoeffect cross sections, K-jump ratios and total to K-shell photoeffect cross section ratios at the K-edges of the elements Cu, Zr, Ag, Sn, Ta, Au, and Pb, from their earlier studies on total attenuation

cross sections [Ramakrishna Gowda et al. (1976), Puttaswamy et al. (1979), (1981<sub>a</sub>), Puttaswamy (1980)]. The derived photoeffect cross sections were in good agreement with corresponding values of Scofield (1973). They obtained empirical relations for K-edge cross sections and ratios, which were found to reproduce the values to an accuracy better than 1%.

Umesh et al. (1981) studied the total attenuation cross sections of a number of compounds and from the measured data they derived the incoherent scattering cross sections of 26 (low and medium  $Z$ ) elements for energies in the range 279.2 to 1115.5 keV. The compounds used are LiOH, MgO, NaF, NaCl, NaNO<sub>2</sub>, KCl, NiO, CuO, TiO<sub>2</sub>, NaHCO<sub>3</sub>, NaNO<sub>3</sub>, MnO<sub>2</sub>, CuCl, CrO<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>CO<sub>3</sub>, KBr, RbCl, ZrO<sub>2</sub>, SrF<sub>2</sub>, KH<sub>2</sub>PO<sub>4</sub>, Na<sub>2</sub>SO<sub>4</sub>, AgCl, BaO, KI, CdI<sub>2</sub>. The attenuation cross sections of Al, Cu, Zr and Ag foils also have been measured. The binding effects of electrons were discussed.

Umesh et al. (1982) extended their work and measured total attenuation coefficients of some compounds containing rare earth and high  $Z$  elements and derived the incoherent scattering cross sections of several constituent elements in the energy range 279.2 to 1115.5 keV. In the measurement of the total attenuation cross section, an extrapolation method was used to correct for the multiple scattering effects. The compounds La<sub>2</sub>O<sub>3</sub>, CeO<sub>2</sub>; PrO<sub>2</sub>, Nd<sub>2</sub>O<sub>3</sub>, Sm<sub>2</sub>O<sub>3</sub>, Gd<sub>2</sub>O<sub>3</sub>, Dy<sub>2</sub>O<sub>3</sub>, HO<sub>2</sub>O<sub>3</sub>, Er<sub>2</sub>O<sub>3</sub>, Ta<sub>2</sub>O<sub>5</sub>, (HCOO)<sub>2</sub>Pb, and Bi<sub>2</sub>O<sub>3</sub>, were used in the investigation. The incoherent scattering cross sections of La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, Er, Ta, H, Pb, and Bi have been derived.

Nageswara Rao et al. (1984) reported the measurement of total attenuation coefficients of elements C, Al, S, Ni, Cu, Zn, Se, Mo, Ag, Cd, In, Sn, Sb, Te, I, Hg, Pb and Bi, and compounds H<sub>2</sub>O, NaCl, CaF<sub>2</sub>, TiO<sub>2</sub>, NH<sub>4</sub>NO<sub>3</sub>, ZnO, NaNO<sub>3</sub>, KNO<sub>3</sub>, KH<sub>2</sub>PO<sub>4</sub>, GaAs, CaTe, KBrO<sub>3</sub>, MnSO<sub>4</sub>, H<sub>2</sub>4O, CdCl<sub>2</sub>, ZnTe, Sr(NO<sub>3</sub>)<sub>2</sub>, InSb, (CH<sub>3</sub>COO)<sub>2</sub> CO<sub>4</sub> H<sub>2</sub>O, CuSO<sub>4</sub> 5H<sub>2</sub>O,

Ba(NO<sub>3</sub>)<sub>2</sub>, ThO<sub>2</sub>, FeSO<sub>4</sub> · 7H<sub>2</sub>O; CoSO<sub>4</sub> · 7H<sub>2</sub>O, K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>, NaWO<sub>4</sub> · 2H<sub>2</sub>O, Na<sub>2</sub>B<sub>4</sub>O<sub>7</sub> · 10H<sub>2</sub>O, UO<sub>2</sub>(COO)<sub>2</sub> · 3H<sub>2</sub>O, HgI<sub>2</sub>, Bi(NO<sub>3</sub>)<sub>3</sub> · 5H<sub>2</sub>O in the energy range 32.1 to 661.6 keV, using a NaI(Tl) scintillation spectrometer in a good geometry setup. From the data obtained for the compounds, they have derived total attenuation cross sections for 15 elements, using mixture rule. From these values of total attenuation cross sections they have derived the photoeffect cross sections, for low and high *Z* elements, by the subtraction method, in the energy range 30 to 280 keV. Analyses in terms of effective atomic numbers and photoelectric cross sections were given.

Umesh et al. (1984) have measured total attenuation cross sections of 38 compounds at energies 1170 and 1330 keV, in the same method as described in Umesh et al. (1981, 1982). The whole-atom integral incoherent scattering cross sections were derived for 38 elements using mixture rule and an extrapolation method.

Umesh and Ranganathaiah (1984) devised a simple method for the determination of the photoeffect cross sections of elements from the measured total attenuation cross sections of their compounds. The investigation involves the measurement of total attenuation cross sections of the compounds AgCl, KI, BaO, La<sub>2</sub>O<sub>3</sub>, CeO<sub>2</sub>, PrO<sub>2</sub>, Nd<sub>2</sub>O<sub>3</sub>, Sm<sub>2</sub>O<sub>3</sub>, Gd<sub>2</sub>O<sub>3</sub>, Dy<sub>2</sub>O<sub>3</sub>, HO<sub>2</sub>O<sub>3</sub>, Er<sub>2</sub>O<sub>3</sub>, Ta<sub>2</sub>O<sub>5</sub>, (HCOO)<sub>2</sub>Pb, and Bi<sub>2</sub>O<sub>3</sub>. From these values the total photoeffect cross sections of elements have been derived in the energy range 514 to 1332.5 keV, using the new method.

Parthasaradhi (1985) carried out total attenuation cross section measurements near the edges of some elements and compounds. Analysis in terms of Photoelectric cross sections was given. Deviations were reported by comparing the data obtained for compounds with the available theoretical values.

Reddy et al. (1985) made a study of total attenuation cross sections of several alloys in the energy range 32.1 to 661.6 keV. A NaI(Tl) detector

was used in a good geometry setup. The photoeffect and scattering cross sections at appropriate photon energies were obtained by using the subtraction method. The total and partial effective atomic numbers were also derived. The results were in agreement with the theoretical values.

Umesh et al, (1985) measured total attenuation cross sections of several compounds and by applying the mixture rule the total attenuation cross sections of some constituent elements were derived, at the energy 145.4 keV, in a good geometry setup. Photoeffect cross sections of the corresponding elements have been derived from their total attenuation cross sections by using the subtraction method. The compounds used were  $\text{NaNO}_2$ ,  $\text{NaNO}_3$ ,  $\text{La}_2\text{O}_3$ ,  $\text{CeO}_2$ ,  $\text{PrO}_2$ ,  $\text{Nd}_2\text{O}_3$ ,  $\text{Sm}_2\text{O}_3$ ,  $\text{Gd}_2\text{O}_3$ ,  $\text{Dy}_2\text{O}_3$ ,  $\text{Ho}_2\text{O}_3$  and  $\text{Er}_2\text{O}_3$ .

Bradley et al. (1986) made photon absorptiometric studies of some elements, mixtures and substances of biomedical interest in the energy range 33.1 to 662 keV. The elements C, Al, S, compounds  $\text{H}_2\text{O}$ ,  $\text{CaCO}_3$ , and substances dry bone, bone standard, wax, polyethylene, polyisoprene, dried lean meat, fat, coconut oil, corn oil, ghee were used.

Seetharami Reddy et al. (1987) used a high resolution Si(Li) detector to resolve the gamma ray doublet with 79.623 and 80.999 keV energies of  $\text{Ba}^{133}$  source. The total attenuation cross sections of Cu, Pt and Au were measured for the above gamma rays. They have adopted the experimental setup and method of measurement reported by Radhakrishna Murty et al. (1985), Smiles et al. (1982) and Kane et al. (1977). They have measured total attenuation coefficients at the doublet energies and obtained the cross section for the intensity weighted average energy 80.905 keV by using two methods. In the first method they interpolated the cross section corresponding to the lower edge (80.923 keV) of Scofield (1973) down to 80.905 keV, which yielded a highly under estimated value for cross section. In the second method, the lower edge was totally neglected and the data of Scofield below the upper edge (81.57 keV) extrapolated to 80.905 keV. The value

of cross section so obtained is lower than the corresponding value of Storm and Israel (1970) by about 12%. The results except for Aii at 80.905 keV were in agreement with values of Storm and Israel (1970) and Scofield + Hubbell et al. (1975, 1979). They have reported a steady fall in total attenuation cross sections at 80.905 keV with increase of  $\mu$ t. The disagreement at 80.905 keV is attributed to (1) the dilution of the transmitted intensity due to 79.623 keV photons and (2) effect of the finite level width of Au *K* edge which falls between the doublets.

Ghosh and Das (1990) have measured total attenuation cross sections of several elements with  $Z = 6$  to 92 in the energy range 43 to 1330 keV. mainly in the vicinity of the shell edges, by using a NaI(Tl) detector in a good geometry setup. The angle of acceptance for the scattered photon was  $0.3^\circ$ .

Umesh et al. (1992) measured total attenuation cross sections of the oxides of rare-earth elements such as La, Ce, Pr, Nd, Sm, Gd, Dy, Ho and Er and also  $\text{NaNO}_3$ , and  $\text{NaNO}_2$  in a narrow beam geometry setup at 323 keV. The total attenuation cross section for oxygen was obtained as the difference in  $\text{NaNO}_3$  and  $\text{NaNO}_2$  cross sections. Using this, the total attenuation cross sections of the individual lanthanides were obtained with the aid of mixture rule. Photoeffect cross sections were derived from these values, by subtracting the scattering contributions.

Kefi et al. (1992) measured the total attenuation cross sections of Pd, Ag, Cd, In, Sn, I and Xe for energies between 15 and 45 keV. A power law was used to fit the experimentally observed mass attenuation coefficients as a function of the photon energy. They have evaluated the real part of the anomalous scattering factor from the data obtained. By using an analytic expression involving Gauss hypergeometric functions they calculated the dispersion term.

Recently, in this laboratory, new methods have been formulated to

derive coherent, incoherent and photoelectric cross sections of elements by measuring the total attenuation cross sections of their mixtures, keeping them at two different positions ( $P_1$  and  $P_2$ ) in a good geometry setup by using a well type NaI(Tl) crystal detector. The salient feature of this method is that it does not depend on any theoretical assumptions or values but only on experiment. Position  $P_1$  is outside the detector, at a reasonable distance from it, such that no scattered photons can reach the detector. Position  $P_2$  is inside the well of the detector. When the sample is inside the well of the detector almost all the scattered photons enter the detector. The attenuation cross section measured with the sample at  $P_1$  contains contributions due to all possible types of interactions at the energy of interest, where as when the sample is inside the well, contributions from various processes varies with the region of the spectrum selected for calculation. Shylaja Kumari et al. (1994), Anasuya et al. (1994) and Channe Gowda et al. (1994) have used these methods to calculate the incoherent, photoeffect and coherent scattering cross sections respectively, of elements.

### **1.3 Applications of Radiation**

Ionising radiations and their sources find extensive and vital applications in several fields of Medicine, Biology and Industry. The technological developments along with the availability of Radio-active sources with fairly long life and sufficiently high energy have further expanded the fields of application [Hubbell (1990), Jackson and Hawakes (1981), Gerard (1992) Machi (1993), Butterweck (1993)]. The attenuation coefficients provide valuable informations of medical significance [Phelps et al. (1975)]. The importance of the study of photon attenuation coefficients has increased considerably by the development of X-ray scanner and its applications in medical diagnosis and treatment planning [Hounsfield (1973), Brooks and Dichiro (1976)].

## 1.4 Motivation for the current work

A survey of the literature shows that even though a good deal of experimental work has been done on the measurement of total attenuation coefficients, the data available is still incomplete and inadequate to meet its mounting demand in various fields of radiation applications. The survey also reveals the fact, that very few measurements have been reported which are motivated towards the biologically important molecules. So far no exclusive experimental data have been reported on compounds like *amino acids* and *sugars* which are the fundamental building blocks of any living cell.

### 1.4.1 Aminoacids and Proteins

Amino acids when connected together by peptide bonds, form unbranched long chains known as proteins. It is the difference in the sequence of arrangement of different amino acids that ultimately differentiates various proteins from one another.

Proteins are the primary substances of life and form the major bulk of any living matter. Every cellular activity has its roots in one or more proteins and every facet of growth is a result of changes in proteins.

### 1.4.2 Sugars

Sugars (monosaccharides) are the simplest form of carbohydrates. They are very important in the chemical, biological, nutritional and medical fields. Also they are extensively used in food, textile, oil drilling and thermal as well as nuclear power industries.

Carbohydrates in the form of sugars and starch constitute a major part of the total caloric intake of human beings and most animal life including many microorganisms. They play an important role in the energy metabolism of both animal and plant cells. In addition to it, they play a

vital structural role in both animal and plant cells. Polysaccharides like starch are large combinations of simple sugar molecules (Glucose is a common simple sugar).

Sugar (phosphate) attached with nitrogenous bases form nucleotides, which is one of the important structures in the cells of all living organisms. The nucleic acids *RNA* and *DNA* are large polynucleotides. The sugar Ribose forms part of the structure of *RNA* while the sugar Deoxyribose is a structural element of *DNA*. In the form of Cellulose and Pectin, sugars form important structural elements in the plant cells

### ***Motivation:***

The motivation for the current work arose from the frequent and vital medical and biological applications of ionizing radiations and their sources, which necessitates a detailed knowledge of total attenuation cross sections of biologically important compounds. In spite of the importance of aminoacids and sugars in any biological system, it is learned that they have not yet been subjected to serious photon attenuation coefficient study. So a thorough investigation of the total attenuation cross sections of most of the aminoacids and several sugars has been made in the current study. In view of the importance of these quantities, a *High-Purity Germanium detector* (HPGe) having good resolution and optimum efficiency was employed for the measurement, in a *good geometry setup*. The energy range 30 to 1500 keV, which is found to be most useful in medical and biological fields, was selected for the current study.