CHAPTER I

INTRODUCTION

1.1. Introduction

The chapter deals with various processes of interaction of gamma radiation with matter with particular reference to theoretical aspects of photoelectric effect and coherent scattering, various experimental methods for determining the K shell photoelectric parameters and anomalous scattering factors, and lastly with the scope for further study and the outline of the present work.

1.2. Interaction of gamma radiation with matter

Interaction of gamma radiation with matter has been experimental and theoretical interest over the past several decades and there is a renewed interest in recent years in this field because of its application in various fields such as X ray fluorescence (XRF), crystallographic studies, design of nuclear reactors, material...
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science, radiation biology, medical physics, agriculture, forensic science and industry [1-8].

Usually photon interaction with an atom takes place with the atomic electrons or with the nucleus. The processes are: Rayleigh scattering, photoelectric effect, Compton scattering, Pair production, nuclear Thomson scattering, Delbruck scattering, nuclear Resonance scattering, etc. [9–11]. Some of these processes of gamma ray interaction with matter are briefly described below.

i. Rayleigh scattering

In this process, the incident photon is scattered by the bound electrons without the loss of energy. This is elastic coherent scattering and is significant in heavy elements at and above 0.1 MeV.

ii. Nuclear Thomson scattering

In this process, the incident photon is elastically scattered by the coulomb field of the nucleus. However due to the large mass of the nucleus, the effects are small but measurable.

iii. Photoelectric effect

In this process, the complete absorption of the incident photon by the atom takes place with ejection of a bound electron. This effect is predominant in all medium and high Z elements for photon energies less than 100 keV.
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iv. The Compton scattering

The Compton scattering takes place between the incident gamma photon and an electron in the atom. In this process, the incident gamma photon gives a part of its energy to an atomic electron and gets scattered. The electron is ejected out of the atom and depending on the angle of scattering the energy of the ejected electron varies from zero to the large fraction of the gamma energy. This is an inelastic scattering process, predominant for intermediate energy and medium Z elements.

v. Pair production

In this process, the incident gamma photon is completely absorbed in the coulomb field of the nucleus giving rise to the formation of electron–positron pair. This process takes place when incident photon energy exceeds 1.02 MeV (twice the rest mass energy of an electron). The cross section for pair production is proportional to the square of the atomic number of the target atom and increases with the incident photon energy.

vi. Nuclear Resonance scattering

This is a unique process amongst all gamma ray interactions and involves excitation of nucleus to a higher level by absorption of photon with subsequent reemission of the photon with the same energy. In principle, this resonance scattering process requires the establishment of resonant condition between the absorbing nuclei and the incident radiation.
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The interaction of gamma radiation with matter in the energy range from few keV to few MeV is predominantly through three processes, namely, photoelectric effect, the Compton scattering and pair production. Figure 1.1 shows the plot of $Z$ of the absorber as a function of energy $\hbar \nu$ for the three interaction processes indicating the regions of $Z$ and energy over which these processes predominate [12]. The present study is essentially involves the photoelectric effect.

![Figure 1.1. Plot of $Z$ of the absorber as a function of energy of interaction processes](image)

When a narrow beam of gamma photons passes through matter in bulk, the intensity of the incident beam undergoes attenuation. Its intensity decreases exponentially because of absorption and scattering of photons. If $I_o$ is the incident intensity of the collimated beam of gamma photons, then intensity of the transmitted beam $I_t$ after traversing through a thickness of the absorber $t$ (cm) is given by

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\[ I_i = I_0 e^{-\mu t}, \quad (1.1) \]

where \( \mu \) (cm\(^{-1} \)) is called the total linear attenuation coefficient. This total linear attenuation coefficient is due to various processes and can be expressed in terms of contribution of individual processes as

\[ \mu = \mu_{pe} + \mu_{coh} + \mu_{incoh} + \mu_{pp}, \quad (1.2) \]

where \( \mu_{pe}, \mu_{coh}, \mu_{incoh} \) and \( \mu_{pp} \) are the attenuation coefficients for the photoelectric absorption, the coherent (Rayleigh) scatterings, the incoherent (Compton) scatterings and for the pair productions. However, the thickness of the target can also be expressed in terms of areal density \( \rho t \) (g/cm\(^2 \)) and equation 1.1 can be rewritten as

\[ I_i = I_0 e^{-\left( \frac{\mu}{\rho} \right) t}, \quad (1.3) \]

where \( \mu/\rho \) (cm\(^2\)/g) mass attenuation coefficient. In both experimental and theoretical work the values are expressed in terms of mass attenuation coefficient rather than in terms of linear attenuation coefficient.

The mass attenuation coefficient is related to total cross section \( \sigma \) (barns/atom) by

\[ \sigma_{\mu\mu}(E) = \left( \frac{\mu}{\rho} \right) \times A \times 10^{24} \times \frac{1}{N_0 \ t}, \quad (1.4) \]

where \( A \) is the atomic mass number of the target atom and \( N_0 \) is the Avogadro number. Again, the total cross section \( \sigma_{tot} \) can be expressed in terms of the individual processes as

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\[ \sigma_{\text{tot}} = \sigma_{\text{PE}} + \sigma_{\text{coher}} + \sigma_{\text{coh}} + \sigma_{\text{pp}} \]  

Thus by experimentally measuring the incident and transmitted photon intensities, we can determine the total cross section for the target atom.

1.3. Theoretical aspects of absorption and scattering process

The main aspect of our investigations is measurement of photoelectric cross section over a wide range of energy for the elements of high Z value. The real and imaginary parts anomalous scattering factors are related theoretically to the variation of photoelectric cross section as a function of energy. So a brief survey about the photoelectric effect and the coherent scattering are made.

i. Photoelectric effect

This effect is predominant in all medium and high Z elements for photon energies less than 100 keV. In this process, complete absorption of the incident photon takes place. If the incident gamma photon of energy \( h\nu \) is larger than the binding energy \( E_b \) of the electron in a shell, the incident photon energy is completely absorbed by the atom and an electron from the shell is ejected out of the atom with kinetic energy \( E_e \) given by

\[ E_e = h\nu - E_b, \]  

If the energy is less than the binding energy of the electron then the shell does not contribute to photoelectric effect. When the photon energy is nearly equal to the binding energy of the shell then the photoelectric cross section shows a sharp increase.
at the edges. So the photoelectric cross section considered as a function of photon energy gives a sawtooth structure with the appearance of a sharp increase at the binding energies of the various electron shells in the atom. Figure 1.2. as a typical case, shows a plot of photoelectric cross section as function of energy, exhibiting sharp increase at M, L and K binding energies, for tungsten.

In the photoelectric absorption process, the most important contributor to the photoelectric cross section is the most tightly bound K shell electron (~ 80 %). If the energy of the incident photon is greater than the K shell binding energy of the target atom, the total photoelectric cross section is the sum of the cross section due to K, L, M, N,... shells and if the energy of the incident photon is less than the K shell binding energy, then the total photoelectric cross section is due to the L, M, N,... shells (excluding the K shell). The vacancy created in the K shell is filled by the electrons from the higher shells thereby emitting characteristics X ray photons or electrons; emission of the X ray photons is called X Ray Fluorescence (XRF) and the emission of the electrons is called the Auger process respectively. The emission of X ray characteristics of an element is made use in elemental analysis in biological specimens, agriculture, forensic science, medicine, etc.
The studies of accurate values of total cross sections find variety of applications in various fields. In medical and pharmaceutical fields, the gamma attenuation provides information about the functioning of organs and tissues of human body. The X ray tomography produces images of thin slices of human tissues and provides 3-D information of X ray absorption through normal and cancerous cells. The high energy gamma rays are used to kill the cancerous cells. Also, the complex structures of DNA, RNA, genes, etc are studied by using the irradiation and attenuation methods. The uniformity of the packed tablets and filled capsules, in pharmaceutical industry, is checked by the gamma attenuation technique.
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Theoretical aspects

The main features of the photoelectric effect were explained by Einstein with the quantized radiation hypothesis. Later on with the advent of quantum mechanics and quantum theory of radiation, theoretical evaluations of photoelectric effect have been made using various approximations. These theoretical investigations have been reviewed by several investigators Hall [13], Hulme et al. [14], Heitler [15], Bethe and Salpter [16], Pratt et al. [17], Jackson and Hawkes [4]. In many of the above theoretical studies various quantitative approaches and approximations are considered in deriving the expression for the photoelectric cross sections. Some of them are discussed below.

a. Nonrelativistic case

The photoelectric effect involves a transition of an electron from a bound state in the atom to a continuum state. Since the K shell contributes predominantly, most calculations involve K shell photoelectric cross sections only. In deriving the nonrelativistic formula, the nonrelativistic hydrogen like wave function in a central potential for both the bound and continuum states is used along with the nonrelativistic form of the matrix element. For the approximate treatment of the continuum wave function, the Born approximation is used and it is valid at photon energies well above the absorption edge and for $Z\alpha \ll 1$ where $\alpha$ is the fine structure constant ($= e^2/\hbar c$).
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The transition probability per unit time for the K shell photoelectric interaction is written as

\[ \omega_k = \frac{2\pi}{\hbar} |H_{fi}|^2 \rho(E) dE, \]  
(1.7)

where \( \rho(E) dE \) is the number of final states available in the energy region \( E \) and \( E+dE \) and \( H_{fi} \) is the matrix element for the transition between the initial and final states of the electron.

The ratio of \( \omega_k \) to the incident flux gives the differential cross section, \( d\sigma_k / d\Omega \), which, when integrated over all the angles with respect to the direction of the incident photon, gives an expression for the total K shell photoelectric cross section \( \sigma_K \); Heitler [15] gives

\[ \sigma_k = \alpha^2 \frac{Z^2}{\left(\frac{\hbar}{mc^2}\right)^2} \text{cm}^2/\text{atom}, \]  
(1.8)

where \( \phi_s = \frac{8\pi}{3} \left(\frac{e^2}{mc^2}\right)^2 \) = 6.651 \times 10^{-25}, is Thomson scattering cross section.

When the photon energy is nearer the threshold energy, the Born approximation is not applicable and equation (1.8) is invalid. Using hydrogen-like wave function and limiting the angular momentum change of the electron to \( \hbar / 2\pi \), Stobbe [18] obtains the expression

\[ \sigma_k^S = \sigma_k \times f(x), \]  
(1.9)

where \( \sigma_k \) is given by equation (1.8) and \( f(x) \) is the correction factor to the Born approximation given by
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\[ f(x) = 2\pi \left( \frac{E_b}{\hbar \nu} \right)^{\frac{1}{2}} \frac{\exp \left( -4x \cot^{-1} x \right)}{1 - \exp (-2\pi x^2)}, \quad (1.10) \]

Here \( x \) is the ratio of initial orbital velocity of the electron to the final velocity of the photoelectron, given by

\[ x = \left[ \frac{E_b}{\hbar \nu - E_b} \right]^{\frac{1}{2}}. \quad (1.11) \]

For photon energies close to an absorption edge, \( \hbar \nu \approx E_b \), the function \( f(x) \) is given as

\[ f(x) = e^{-4} \left( \frac{E_b}{\hbar \nu} \right)^{\frac{1}{2}} \left( 1 + \frac{1}{x^2} \right)^{\frac{1}{2}} = e^{-4} \left( \frac{\hbar \nu}{E_b} \right)^{\frac{1}{2}}, \quad (1.12) \]

and for photon energies, \( \hbar \nu >> E_b \), \( f(x) \) is given as

\[ f(x) = \frac{1}{x} \left( \frac{E_b}{\hbar \nu} \right)^{\frac{1}{2}} = 1, \quad (1.13) \]

and hence

\[ \sigma_x = \alpha^2 2^{\frac{1}{2}} \frac{Z^3}{\hbar \nu / m_e c^2} = \sigma_x \quad (1.14) \]

It may be noted that there exists the so called exact non-relativistic cross sections which do not neglect retardation. However, it differs from Stobbe's results by the order of \( \beta^2 (\approx v^2 / c^2) \) and the corrections of this order also results from the use of relativistic Dirac formulation. Therefore, Stobbe's cross section (\( \sigma_x^{St} \)) is regarded as a pure non-relativistic evaluation. However, this is fairly valid, apart from a screening correction, for light elements and low energy photons.

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Grodstein [19] tabulated the X-ray attenuation coefficient from 10 to 100 keV (typical energies) for 24 elements along with few compounds. Gavrila [20, 21] examined the Born approximation and obtained the expression for total and differential photoelectric cross section applicable only for small Z. Pratt [22] obtained the total cross section for the photoelectric effect from K shell of an atom of arbitrary change in the limit of high energies. He used approximate coulomb wave functions and added a term for Stobbe's correction factor and another for coulomb wave function and evaluated the expression for total photoelectric cross section. Using nonrelativistic Hartree–Slater potential function (incorporating all polarization effects), Nagel [23] deduced the expression for K shell photoelectric cross section. Further, Hultberg et al. [24] made the theoretical calculation of K shell photoelectric cross section for various elements using Nagel's expression. Manson [25] showed that reasonable results could be obtained with the use of Hartree–Slater model.

b. Relativistic case

When the energy of the incident photon is of the order of $mc^2$ or greater, then the relativistic wave function is incorporated with the transition matrix element. In the case of hydrogen like wave function Stobbe obtained the cross section for K shell photoelectric absorption as

$$\sigma_k = \alpha^2 \frac{Z^5}{h^2 (2\pi)^2} \times 2\pi \left( \frac{E_b}{h \nu} \right)^2 \frac{\exp\left(\frac{-4x \cot^{-1} x}{1 - \exp(-2\pi)}\right)}{1 - \exp(-2\pi)},$$

(1.15)
This equation leads to very low photoelectric cross sections compared with experimental results.

Using Sauter–Born approximation, Sauter and Stobbe obtained the expression for K shell photoelectric cross section as

\[
\sigma_K = \left[ \alpha Z^2 \phi_0 \frac{1.5}{(E)} \left( \frac{m c^2}{h \nu} \right)^4 (\nu^2 - 1)^{1/2} \left( 4 + \frac{\nu (\nu - 2)}{\nu + 1} \left( 1 - \frac{1}{2\nu \sqrt{\nu^2 - 1}} \ln \frac{\nu + \sqrt{\nu^2 - 1}}{\nu - \sqrt{\nu^2 - 1}} \right) \right) \right] \times 2\pi \left( \frac{E}{h \nu} \right)^{1/2} \exp \left( -4x \cot^{-1} x \right) \frac{1}{1 - \exp(-2\pi x)}.
\]

This equation is not valid for heavy elements.

Hulme et al. [14] gave the exact calculation of the K shell photoelectric cross section by considering the relativistic effects of the electron and the screening effects and have calculated the cross section for \( Z = 26, 50 \) and 84 at 0.354 and 1.133 MeV.

Hall and Sullivan [26] used the wave function in powers of the photon wavelength and calculated the K shell cross section for all the low \( Z \) elements for energies greater than 2 MeV and multiplying a factor of 5/4, to the K shell photoelectric cross section was found to be fairly good for low \( Z \) elements.

With the development of nuclear physics, much interest in the experimental and theoretical work of photoelectric cross section began, as in much of the aspects, the knowledge of photoelectric cross section was essential.

Developments in the theoretical work suggested that the differential photoelectric cross section in the lower perturbation theory is given by

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{photo}} = \frac{4\pi^2 \alpha h^2}{m^2 \omega} \sum |M|^2, \quad (1.17)
\]

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where $\omega$ is the angular frequency of the incident radiation, $M$ is the matrix element related to the atomic form factor $f(q, Z)$. The factor $\sqrt{\sum |M|^2}$ represents the average energy over the photon polarization and the sum over the initial and final electron spins and then the total photoelectric cross section is found by integrating the above equation. Due to the complexity in the form of wave functions of initial and final states in the relativistic case, it is difficult to evaluate the cross section containing the matrix elements. Hence, some approximations were made while evaluating the equation and thus different researchers used different approximations and models.

The calculation of the matrix element is complicated as it contains the wave function of the entire atom (because the incident photon interacts with atom in the photoelectric process) and hence in Hartree–Fock–Slater model, single electron wave function approximation is used. Therefore, in practice the case of a single atom containing single electron (hydrogen or hydrogen like) is considered for all the calculations by assuming that the incident photon interacts with the single electron described by its wave function. In this model, the potential function is written as,

$$V_i(r) = -(Z - S_i) \frac{e^2}{r} + V_{oi},$$  \hspace{1cm} (1.18)

where $S_i$ is the inner screening constant and $V_{oi}$ is the outer screening constant. If the potential is substituted in the Dirac equation for the $i^{th}$ electron the resultant configuration is simply hydrogen like wave function with charge $(Z-S_i)$ and the energy Eigen value corresponding to the hydrogen like wave function added to $V_{oi}$. While calculating the photoelectric cross section, the initial bound state of the electron is
described by the hydrogen like wave function with the principle quantum number $n$ and nuclear charge $(Z-S_n)$. If the quantum of energy $hv$ of the incident radiation exceeds the ionization energy $I_n$ of the atom, then the electron is raised to a state of continuum and thus leaves the atom. Then the total energy $E$ of such a photoelectron is given by

$$E = hv - I_n,$$

(1.19)

At very large radial distances the kinetic energy of the electron equals $E$ and at intermediate distances it is the sum of kinetic and potential energy. Thus the approximate wave function is hydrogen like with nuclear charge $(Z - S_n)$ and the total energy is

$$E - V_{oi} = hv - \frac{(Z - S_n)^2 e^4 m}{2\hbar^2 n^2},$$

(1.20)

The use of hydrogen like wave function is a good approximation for the photo ejection of an inner electron from an atom with fairly high $Z$ and this is used in almost all the calculations of the photoelectric cross section.

ii. Coherent scattering

Coherent scattering is an elastic scattering of photons by the bound electrons of the atom. Though in this process the incident photon is scattered without change of energy, this process is characterized by the anomalous scattering factors, which are related theoretically to variation of photoelectric cross section as a function of energy. So, by our experimentally determined photoelectric cross section over a range of...
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photon energy, anomalous scattering factors can be evaluated. In view of this, we give a brief review of the coherent scattering.

Coherent elastic scattering is due to bound electrons in the atom which have extended charge distribution. As a result of a small phase difference between the initial and final states of the photon, the scattering amplitude is a function of angle of scattering. The differential scattering cross section \( \frac{d\sigma_{\text{coh}}}{d\Omega} \) is given by

\[
\frac{d\sigma_{\text{coh}}}{d\Omega} = \frac{d\sigma}{d\Omega} \times |f(q, Z)|^2. \tag{1.21}
\]

Here, \( \frac{d\sigma}{d\Omega} \) is the differential Thomson scattering cross section and is given by

\[
\frac{d\sigma}{d\Omega} = \frac{e^2}{2} (1 + \cos^2 \theta), \tag{1.22}
\]

and \( f(q, Z) \) is the atomic form factor. The atomic form factor is expressed, in terms of electron charge distribution [27], as

\[
f(q, Z) = \int \rho(r) \exp(iq \cdot r) d^3r, \tag{1.23}
\]

where \( \rho(r) \) is the electron charge density at \( r \). The charge density \( \rho(r) \) can be expressed in terms of \( f(q, Z) \) using the inverse Fourier transform as

\[
\rho(r) = (2\pi)^3 \int f(q, Z) \exp(iq \cdot r) d^3q, \tag{1.24}
\]

For an atom having symmetric charge distribution \( f(q, Z) \) as given by Debye and Pirenne [28] can be expressed as

\[
f_0(q, Z) = 4\pi \int_0^{\infty} \rho(r) \frac{\sin(qr)}{qr} r^2 dr, \tag{1.25}
\]

where \( f_0 \) is called as the normal coherent scattering factor.

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These form factors are derived on the assumption that the photon energy is large compared with the binding energies of the electrons in the atom. When the energy of the incident photon approaches the absorption edge of any one of the bound electrons, the expression of the form factor has to be modified. It may be expressed as [29]

\[ f = f_0 + f' + i f'', \tag{1.26} \]

where \( f_0 \) is the Thomson scattering factor, \( f' \) and \( f'' \) are referred to as the real and imaginary parts of the anomalous scattering factors. The real part \( f' \) corresponds to dispersion and the imaginary part \( f'' \) corresponds to absorption.

The imaginary part \( f'' \) of the form factor at any fixed photon energy \( E_s \) is related to the photoelectric absorption cross section \( \sigma_{PE} \) at that energy through the relation [30]

\[ f'' = \frac{E_s}{2hc} \sigma_{PE}, \tag{1.27} \]

where \( h \) is the Planck's constant, \( c \) is the velocity of light, \( r_0 \) is the classical radius of electron and \( E_s \) is the photon energy of interest. Thus by determining the photoelectric cross section at various photon energies, the imaginary form factor, \( f'' \), of the atom can be determined as a function of energy.

The real part of the anomalous scattering factor \( f'(E_s) \) at energy \( E_s \) is related to the variation of the imaginary part of the anomalous scattering factor with energy \( E \) by the dispersion relation.
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\begin{equation}
\frac{d\sigma_{\text{coh}}}{d\Omega} = \frac{d\sigma_T}{d\Omega} \times [f(q, Z)]^2,
\end{equation}

where \(d\sigma_T/d\Omega\) is the differential Thomson scattering cross section and is given by

\begin{equation}
\frac{d\sigma_T}{d\Omega} = \frac{r_e^2}{2} \left(1 + \cos^2 \theta\right),
\end{equation}

and \(f(q, Z)\) is the atomic form factor.

Therefore, by numerical integration over all the angles, the total coherent scattering cross section is given by

\begin{equation}
\sigma_{\text{coh}} = \pi r_e^2 \int_{-1}^{1} \left(1 + \cos^2 \theta\right) \times [f(q, Z)]^2 d(\cos \theta),
\end{equation}

\begin{equation}
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\end{equation}

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The atomic form factor formalism is extensively used for analysis of data of X-ray scattering experiments [31]. In fact, it is mainly used in the study of structure of macromolecules, in the study of wave-fields in large inorganic crystals and the interpretation of images formed in X-ray topography experiments, in the study of phase transformations and solid state reactions, in the study of the local environments for molecules and in condensed matter using extended X-ray absorption fine structure (EXAFS) techniques, in the investigations of the composition of materials using X-ray fluorescence spectroscopy (XRF), electron probe microanalysis (EPMA) and proton induced X-ray emission (PIXE), in the studies of crystalline materials in which thermal motion or lattice disorder contributes significantly to the X-ray scattering, in the study of changes in composition and crystal structures in materials subjected to high pressures or temperatures using energy dispersive X-ray diffraction (EDXRD) and in the study of magnetic scattering by electronic spins with materials.

Extensive theoretical investigations have been carried out by many researchers for evaluating various photoelectric parameters and the anomalous scattering factors for various Z values. Tables of X-ray attenuation coefficient as compiled by Storm and Israel, McMaster et al., Hubbell et al., Henke et al., Creagh et al., Cullen et al., Chantler et al., and so on are just purely theoretical, experimental or a mixture of theoretical and experimental information. Some of them are listed below.

Using relativistic electron wave function in a screened potential, Pratt et al. [32] calculated the total and differential cross sections for various Z values. Schmickley and Pratt [33] calculated the total photoelectric cross sections in the range
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from M shell binding energy to K shell binding energy using Coulomb, Thomas–Fermi, Kerner–Yukawa central potentials; they used the renormalization theory was to include electron screening. Treating the electrons to be moving in a coulomb field, Brysk and Zerby [34] made the relativistic calculations by developing a computer code. Storm and Israel [35] have given a review of the entire theoretical data on photoelectric cross sections.

Cromer and Libermann [36, 37] have published extensive tabulations of the dispersion correction factors $f'$ and $f''$ using relativistic Dirac–Slater wave function, for photon energies corresponding to $K_{α}$ radiations of Cr, Fe, Cu, Mo and Ag for neutral atoms in the range $3 \leq Z \leq 98$; they used dipole approximation in estimation of the relativistic correction to the high energy limit of forward scattering. Cromer [38] has developed a FORTRAN program for estimating the photoelectric cross sections and the anomalous scattering factors at various X-ray wavelengths.

Henke et al. [39, 40] have tabulated the $f' (\infty)$ values using dipole approximation for atoms $1 \leq Z \leq 94$. Scofield [41] has calculated the photoelectric cross sections using Hartree–Fock approximations for the elements with atomic numbers from $Z = 2$ to 54; and also provided the correction factors for individual atomic sub shell. Creagh and McAuley [42] used relativistic multipole expansion for calculating the anomalous scattering factors. Using the relativistic second order S–matrix, Kissel et al. [43] have developed an accurate method for evaluation of total–atom Rayleigh amplitudes. Kissel and Pratt [44] have calculated the $Z$ dependent and energy independent correction factors for the real anomalous scattering factor $f'$ and
differential elastic scattering cross sections. Wang [45] developed a relativistic dispersion relation, accurate up to the order of $\alpha^2 Z^2$, for the real part of X-ray atomic anomalous scattering factors.

Coherent (Rayleigh) scattering cross sections have been calculated and tabulated by Hubbell and Overbo [46] using relativistic atomic form factors, for all elements from 100 eV to 100 MeV. Tables of incoherent (Compton) scattering cross sections have been tabulated by Hubbell et al. [47]. Berger and Hubbell [48, 49] have developed a program to calculate photon cross-section for scattering, photoelectric absorption and pair-production as well as total attenuation coefficient for any element, compound or mixture, at energies from 1 keV to 100 GeV. In fact Gerward et al. [50] have developed a 'Windows' version of XCOM–WinXCOM to calculate the photon cross-sections.

Cullen et al. [51] have provided photon data library including the entire photoelectric cross sections, $f'$ and $f''$ values for elements with atomic numbers ranging from $Z = 1$ to 100 for the energies ranging from 1 eV to 100 GeV. Using S-matrix formalism, Chatterjee and Roy [52] have computed and tabulated the coherent scattering cross sections (both differential and total scattering cross sections) for the elements having atomic numbers $Z = 13$ to 104, for fourteen commonly used gamma energies between 50 keV and 1.5 MeV. Chantler [53, 54] has made an extensive new calculations and tabulated the atomic form factors, attenuation coefficients, elastic and inelastic scattering cross sections for the elements of atomic number $Z = 1$ to 92, in the energy range from 1 to 10 eV and from 0.4 to 10 MeV. Bremer [55] has calculated...
the energy dependence of the anomalous atomic scattering factors at the K absorption edge for free atoms and molecules. Zhou et al. [56] have provided the computational schemes to calculate the anomalous scattering factors for neon ions. Bergstrom Jr. et al. [57] have investigated the angle dependence of the elastic photon–atom scattering amplitude using full relativistic S matrix calculations. Kefi et al. [58] developed an analytical method to determine the anomalous scattering factors and compared his results with the experimental values for Pd, Ag, Cd, In, Sn, I and Xe elements around their K edges in the energy range from 15 to 45 keV. He has used bremsstrahlung photons emitted by a sealed X ray tube and a crystal monochromator to get monochromatic beam of photons with a resolution of 10 eV at 20 keV.

1.4. Survey of experimental results

Many researchers have determined experimentally the photoelectric cross section and anomalous scattering factors at various energies by various methods. The mass attenuation coefficients are measured by using radioisotopes which emit highly monochromatic gamma / X ray photons. Apart from the radioisotopes, X ray photons from the X ray tubes and synchrotron radiation from the synchrotron sources are also used; as these emit continuous radiations, monochromatic beam is to be selected using crystal monochromator. Though synchrotrons are one of the most successful sources of radiations, intensity of synchrotron radiation decreases rapidly above 50 keV; and hence most of the investigations are confined to low and medium Z elements [59, 60]. However, the third generation synchrotrons such as EPS, APS and Spring-8, provide
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high intensity radiation in the higher photon range also, which can extend investigations to high Z elements. It is seen that more than 50 synchrotron sources are in operation in the world making it the most often used source of radiation for studying interaction of radiation with matter.

The synchrotron facility is expensive to build and maintain, and are not accessible to many investigators due to limited resources. This difficulty can be overcome by using continuous external bremsstrahlung produced by beta particles incident on a target and a very high resolution gamma detector. Such a method has been developed by Nayak and Badiger [61, 62]. A brief account of bremsstrahlung radiation is given below.

It is well known from the classical electromagnetic theory that whenever a charge is accelerated or decelerated, it emits electromagnetic radiation. Such radiation has continuous spectrum and is called bremsstrahlung. Bremsstrahlung was observed by Rontgen in 1905 and by Gray in 1911. Bremsstrahlungs are classified into two types, Internal bremsstrahlung and External bremsstrahlung. When a beta particle is emitted, it may undergo acceleration in the coulomb field of the daughter nucleus and emit bremsstrahlung radiation. This is known as Internal bremsstrahlung. And if a beta particle undergoes acceleration in the coulomb field of nuclei in a material medium, it also emits bremsstrahlung. This is known as external bremsstrahlung. Since the acceleration is proportional to the force experienced by the beta particle the intensity of the external bremsstrahlung is proportional to the square of the atomic number of the target material on which the charged particle is incident. The external

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bremsstrahlung can be stronger than the internal bremsstrahlung. The intensity of the external bremsstrahlung decreases as the photon energy increases and is circularly polarized in the keV region and there is an angular correlation between the incident charged particle and the external bremsstrahlung photons. The information about the various calculations of the bremsstrahlung cross sections and its related data is discussed in detail by Koch and Motz [63]. Several investigations have studied external bremsstrahlung radiations produced by beta particles in thin and thick targets. Sarma and Narshima Murty [64] studied the growth of external bremsstrahlung as a function of energy, produced in radiator foils Al, Cu, Ag, Sn and Pb covering the range of atomic number from 13 to 82 due to absorption of continuous beta rays from \(^{32}\text{P},^{91}\text{Y},^{204}\text{Tl},^{185}\text{W}\) and \(^{169}\text{Er}\). Gopala et al. [65] studied the thick target bremsstrahlung spectra generated by the beta particles of radioactive sources \(^{90}\text{Sr} - ^{90}\text{Y}\) and \(^{90}\text{Tc}\) in the targets of Cu, Mo, Ag, Cd and Pb using NaI(Tl) scintillation spectrometer. Using rare earth permanent magnet (REMP) technology. Luna [66] studied the bremsstrahlung radiation effects in some rare earth permanent magnets. Singh et al. [67] have studied the total bremsstrahlung spectra in thick targets of Al, Ti, Sn and Pb produced by complete absorption of \(^{204}\text{Tl}\) beta particles produced in the photon energy range from 10 – 30 keV using Si(Li) detector.

There are two methods for measuring the photoelectric cross section, direct method and the indirect method. In the direct method, the photoelectric cross section is measured and in the indirect method, first the total cross section is measured and the other scattering cross sections are subtracted from it.

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i. Direct method

The direct method involves four different techniques for the determination of photoelectric cross section and anomalous scattering factors.

a) Photoelectron intensity measurements using β ray spectrometers or scintillation spectrometer: In this method, the number of photoelectrons produced by incident radiation of known intensity is measured using either a β ray spectrometer or scintillation spectrometer; and from this the photoelectric cross section is measured.

b) By study of internal conversion electron intensity: A theoretical relation is derived between the intensity of gamma photons from a radioactive source, the photoelectric cross section and the internal conversion coefficients. By measuring the intensity of internal conversion electrons and the intensity of the gamma photon, the photoelectric cross section is estimated.

c) Coincidence technique: By taking the coincidence count rate between the ejected photoelectron induced by a source of gamma radiation and the characteristic K X rays produced in the target, the K shell photoelectric cross section is estimated.

d) X ray fluorescence method: By measuring the intensity of K X rays from the target in which atoms have undergone photoelectric process due to gamma rays from a source of known strength, the K X ray photoelectric cross section is measured.
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Using these methods (Direct method), various researchers have determined the K shell photoelectric cross sections in various elements, they used radioactive gamma sources.

Using magnetic $\beta$ ray spectrometer, Davidson and Latyshev [68] have determined the photoelectric cross section at 2.62 MeV gamma photons in Pb, Ta, Ag and Cu by measuring the photoelectron intensity. In addition, they have also measured the angular distribution of photoelectrons and atomic number dependence of the photoelectric cross sections. Roos [69, 70] have determined the K shell fluorescence yields of Zr, Nb, Mo, Rb, Pb, Ag, Cd, Sn, Fe, Ni, Cu and Zn by using a NaI(Tl) scintillation detector. Seeman [71] have estimated the K shell photoelectric cross section in lead at 511 keV using the triple coincidence between $\beta^*$ particle, K conversion electron and K X rays. Hultberg and Stockendel [72], and Hultberg [73] have determined the internal conversion coefficient to find the strength of the gamma source and then determined the absolute photoelectric cross section.

Titus [74] determined the photoelectric cross section by detecting the photoelectrons from thin discs of Cu, Mo, Ag, Ta and Au targets at 662 keV gamma rays using a plastic scintillator. Using high resolution $\beta$ ray spectrometers, Blecker et al. [75] and Boyd et al. [76] measured the photoelectric cross section. McCrery et al. [77] have measured the X ray attenuation coefficients, using a Bragg diffraction monochromator, for 26 elements in the energy range of 25 keV to 130 keV.

Parthasaradhi et al. [78] and Ranganathaiah et al. [79] have measured the photoelectric cross section at low photon energies using a well type plastic.

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scintillator. Ranganathaiah et al. [80] have measured the K shell photoelectric cross section using double coincidence between the photoelectrons and characteristic X ray photons in $2\pi$ geometry. Parthasaradhi [81] has measured the photoelectric cross section by subtracting the total coherent and incoherent scattering cross section from the total photon attenuation coefficient near the absorption edges of some elements and compounds. Allwadhi and Sood [82] have measured the K shell photoelectric cross section for intermediate elements in a reflection geometry setup with a 300 µCi source. Arora et al. [83] have measured the K shell fluorescence yield in elements 28 $\leq Z \leq 53$ using a $^{241}$Am source of 100 mCi in reflection geometry. In both the set up heavy shielding was used (for both the source and the detector).

Using Si(Li) detector in a $2\pi$ geometrical configuration Budak et al. [84] have determined the total photoelectric cross section from K X ray fluorescence in Zr, Nb, Mo, Ag, In, Sn and Te at 59.537 keV gamma energy. Karabulut et al.[85] have measured the $K$, $L$ shell and $L$ sub-shell photoelectric cross section at 59.537 keV in a $2\pi$ geometrical set up using a Si(Li) detector spectrometer, for the elements in the range of 40 $\leq Z \leq 52$ and 58 $\leq Z \leq 68$. Using extended X ray floouriscence technique, Polat et al. [86] have measured the K shell photoabsorption jump factors for elements Ag, Cs, Ba and La derived from mass attenuation coefficients. Adopting $2\pi$ geometrical configuration, the K shell fluorescence parameters are determined by Gudennavar et al.[87] for high Z elements (62 $\leq Z \leq 82$) at 123.6 keV gamma energy. Creagh [88, 89] measured real part of the anomalous scattering factors $f'$ values using
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X ray interferometry for F, Na, Si, Cl, K, Ca, Ni, Cu, U and compared their results with the theoretical values.

ii. Indirect or total attenuation method

In this method, the photoelectric cross section is derived by subtracting the contribution of coherent and incoherent scattering from the measured total atomic cross section, under narrow beam geometry setup. This method requires the theoretical knowledge of scattering cross sections. In fact this method is justified for $E < 100 \text{ keV}$ and $Z > 20$, as the contribution due to photoelectric process is predominant in this range compared to the other processes. Detailed bibliographies of such methods are available in the review article of Hubbell [90].

Davisson and Evans [91] were the first to employ the narrow beam geometry setup, which was later employed by many other researchers, using scintillation detector, proportional counter, high resolution HPGe, Si(Li) or Ge(Li) detector spectrometers. Perkins and Dougles [92] have measured photon attenuation cross sections of Uranium for eleven discrete energies in the region 10 to 300 keV, by using a narrow beam geometry setup coupled with Ge(Li) detector. Conner et al. [93] have measured the gamma ray attenuation coefficients in the energy region $88 \ E = 2750 \text{ keV}$ for 24 elements in the atomic range $4 \ Z \ 94$. These results are found to be in good agreement with the theoretical values of Wyard. Henry and Kennett [94] have measured the total photoelectric cross section for 30 discrete energies in the energy region 121 keV to 11 MeV for 9 elements of atomic numbers ranging from 6 to 92.
Excellent agreement, with the theoretical values of Storm and Israel, and of Grodstein, is found below 6 MeV. Gopal and Sanjeevaiah [95] have measured the gamma ray attenuation coefficients for elements from C to Pb at 662 keV, by adopting the counting sequence of Conner et al. [93]. They have also measured the gamma ray attenuation coefficients in C, Al, Cu, Sn and Pb elements in the energy range from 84 to 411 keV. Kane et al. [96] have made the gamma ray attenuation measurements for Mo, Ta and Pb in the energy region from 0.662 to 1.33 MeV. Reddy et al. [97] have determined the photoelectric cross section value below the K edge of Au, Pb, Th and U in the energy range from 30.9 to 55.4 keV. Rao et al. [98] have determined the total photon cross section around the K edge of Zr, Ag, Ta and Th using Ge(Li) detector at discrete energies in the energy range from 5.9 to 400.7 keV. Prasad [99] has made the total photon absorption cross section measurements at 52.4, 60, 72.2 and 84.4 keV for Al, Fe, Mo, Ag, W, and Pt.

Puttaswamy et al. [100] have measured the total absorption cross sections in the elements C, Al, S, Cu, Zr, Sn, Ta, Ag, Au and Pb in the energy region from 5 to 130 keV using a proportional counter and thin NaI(Tl) detectors and the measured values were compared with the values of Miller and Greening and McCrary et al. Gerward [101] determined the X ray attenuation coefficients and atomic photoelectric absorption cross sections of Si in the energy range of 8.048 - 19.608 keV. Lingam et al. [102] have measured the total attenuation coefficients for Ta, W, Au and Pb at six discrete photon energies in the energy range from 32.1 to 279.2 keV using two NaI(Tl) scintillation detectors. Babu et al. [103] have measured the total mass

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attenuation cross sections of fourteen rare earth elements in the energy range from 30 to 662 keV. The derived photoelectric cross section values were compared with the theoretical values of Scofield.

Dreier et al. [104] determined the anomalous X ray scattering factors of Ni, Cu, Zn and Zr close to K absorption edges and of Ta, W, Pt and Au close to L edges by applying the dispersion relation to the absorption spectra. Moshe and Hart [105] have measured the absolute X ray attenuation cross section for Kr in the vicinity of the K edge using EXAFS arrangement employed by synchrotron radiation. By adopting an indirect method, Prakhya et al. [106] have measured the K shell photoelectric cross sections for Tb, Ho, Er and Pt at 84.26 keV gamma energy. Nathuram et al. [107], measured the photoelectric cross sections for low photon energies ranging from 5.9 – 20.16 keV in Be, C, Al, Mg, Si, Cu, Ag and Pb using a Si(Li) detector and the results were compared with the theoretical values of Storm and Israel. Parthasardhi et al. [108] have made the measurement of absolute photoelectric cross section at the K edges of Ti, Ni and L edges of Pt, Au using synchrotron radiation. Rao [109] measured the photoelectric cross section around the K edge of elements of Ce, Er and Yb and around L edge of Gd, Dy, Er, Yb and Pb using NaI(Tl) detector. The estimated results were found to be in good agreement with the theoretical values of Storm and Israel, and Scofield. Using a novel method, Kerur et al. [110], have determined X ray mass attenuation coefficients for Al, Cu, Ag, Lucite, Mylar, Nylon, Teflon at 5.947 keV gamma photons. Millar [111] studied the atomic number dependence of the photoelectric cross section for photons in the energy range
from 4.5 to 25 keV for 13 different elements. Murty et al. [112] have determined the total photon cross section around the K edge for Cu, Sn, Pb and U using Ge(Li) detector, argon and krypton proportional counters on a good geometry setup and also the K shell jump ratios were evaluated by extrapolating the total photon cross section data to the K edge. Canada et al. [113] have determined the Plutonium K absorption energy using $^{152}$Eu gamma ray. It was determined by measuring the Pu mass attenuation coefficient at eleven gamma energy including the K edge of Pu. Varier and Unnikrishanan [114] have measured the attenuation coefficient for Al for X rays in the energy range of 7 – 15 keV. Using NaI(Tl) scintillation detector, by employing modified “good geometry” arrangement at 7 energies ranging from 43 – 152 keV, Machali et al. [115] have determined the photoelectric cross sections for elements Al, Cu, Zn, Ag, Pt, Au and Pb. Tobiyama et al. [116] have made the precise measurement of the coherent bremsstrahlung spectra from an Al crystal and have determined the atomic form factor. Using NaI(Tl) detector, Gowda et al. [117] have measured the total coherent scattering cross section for Bi, Pb, W and Ba at 661.6 keV gamma energy. Turgut et al. [118] have measured the total mass attenuation coefficients for Cu, Cr and their compounds for photon energies between 4.508 and 11.210 keV using Si(Li) detector. Using parametric X ray radiation (PXR), Tamura et al. [119] have measured the mass attenuation coefficient around the K absorption edge of Nb, Zr and Mo.

Using the S matrix approach, Rao et al. [120] measured the Rayleigh scattering cross sections and the anomalous dispersion for Pd, Ag, Cd, In, Sn, Sb, Pt, Au and Pb.
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at an angle of 90° in the X ray region of 5.41 – 8.04 keV. Yashoda et al. [121] have determined the K shell fluorescence cross section experimentally for 10 elements (Pb, Hg, Ir, W, Lu, Tm, Dy, Tb, Gd and Nd) for 661.6 keV gamma rays using NaI(Tl) detector. Tran et al. [122] have compared the X ray mass attenuation coefficient of Si obtained from the X ray extended range technique, from 5 to 20 keV with the theoretical calculations in the energy range of 5 to 50 keV. The discrepancies between the experimental results and theoretical computations are discussed and concluded that no single theoretical computation is able to reproduce over the entire region of 5 to 50 keV. Using a high purity germanium detector Midgley [123] has measured the linear attenuation coefficient for low atomic number material at energies 32 – 66 and 140 keV. Chantler et al. [124, 125] and Tran et al. [126] have determined the imaginary form factor \( f'' \) for Cu and Si respectively in the energy range upto 20 keV using synchrotron radiation. Tran et al. [127] have measured the X ray mass attenuation coefficient and imaginary form factor \( f'' \) for Ag in the energy range of 15 to 50 keV. Using XERT, Smale et al. [128] have made the analysis of X ray absorption fine structures using absolute X ray mass attenuation coefficient for Molybdenum. AppajiGowda et al. [129] have determined the anomalous scattering factors for La, Ce, Pr, Nd, Sm, Gd, Dy, Ho and Er in the energy range from 6 to 85 keV using gamma ray attenuation method. Here they have used monoenergetic gamma sources for measuring the attenuation coefficients. The X ray absorption in the K edge region has been measured on the Cd vapor by Kodre et al. [130] in a sealed temperature cell. Ertugral [131] have determined the K shell cross section and

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K shell fluorescence yields for Ce, Pr, Nd, Sm, Eu and Gd at 123.6 keV photon from $^{57}$Co source using a high resolution Si(Li) detector. Using energy dispersive X ray fluorescence technique, Kaya et al. [132] have measured the K shell absorption jump factors and jump ratios derived from mass attenuation coefficients of Tm, Yb elements from Tm$_2$O$_3$, Yb$_2$O$_3$ compounds and Lu, Hf, Ta, W, Re and O$_2$ in the energy region 56 – 77 keV. Kaya et al. [133] have reported the measurements of the K shell, L shell–subshell and M shell–subshell photoelectric effect cross section for 21 high atomic number elements between Tb and U at 123.6 keV gamma photon. Gomilsek et al. [134] have studied the X ray absorption coefficient of Iodine in the K edge region within a region of 4.3 keV using X ray absorption spectroscopy of Iodine vapor. In a narrow beam good geometry using a high resolution HPGe detector, Mallikarjuna et al. [135] have measured the total attenuation cross section and K shell photoelectric parameters for La, Ce, Pr, Nd, Sm, Gd, Dy, Ho and Er in the energy range 6 – 85 keV. By adopting the gamma ray attenuation method, AppajiGowda and Umesh [136] have determined the anomalous scattering factors for Ta and Pb near L edge in the energy range 6.4 – 24.14 keV. Also, de Jonge et al. [59] have measured the atomic form factors of tin using the synchrotron radiation. Very recently, Gover et al. [60] have made the measurements of the X ray mass attenuation coefficient and imaginary component of the form factors of Copper at 108 energies between 5 to 20 keV using synchrotron radiation.
1.5. **Scope of the present investigations**

From the literature survey, it is to be noted that several investigators have determined the photoelectric parameters and anomalous scattering factors both theoretically and experimentally. But there are very meager experimental determinations of the parameters at and very close to the K edge of the high Z elements have been made, that too with disagreements of nearly 10 – 20 %. This is because there are only a few monochromatic radioactive gamma sources are available and invariably extrapolation and interpolation methods have to be adopted to evaluate the K shell binding energy as well as the increase in the photoelectric cross section at the K edge accurately. Further anomalous scattering factors can be evaluated more accurately if the photoelectric cross section is known as a continuous function of energy, which cannot be achieved using radioactive sources. Though synchrotron radiation provides continuous spectrum of gamma photons, the experimental determinations are limited to 50 keV only which correspond to K edge energies of low and medium Z elements and L edges of high Z elements.

In the present investigations, both the limitations have been overcome by making use of continuous external bremsstrahlung radiations and a high resolution solid state detector. This method in general can be used to measure photoelectric cross section in the energy range from 20 keV to 200 keV. In the present investigations we have measured the photoelectric cross section from 20 – 160 keV and evaluated the photoelectric parameters for eight elements covering the Z values from 64 – 82, Gadolinium (Gd), Dysprosium (Dy), Ytterbium (Yb), Hafnium (Hf), Tantalum (Ta).
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Tungsten (W), Gold (Au) and Lead (Pb), whose K shell binding energies lie in the range from 50 keV to 90 keV.

A weak $^{90}\text{Sr} - ^{90}\text{Y}$ beta source of long half life of 28 years is used as a primary source of beta particles. As $^{90}\text{Y}$ (half life 64 hours) is in secular equilibrium, the intensity of the beta particles remains constant over the duration of our experiments, about 60 hours. These beta particles are made to fall on a thin nickel foil in which continuous external bremsstrahlung (EB) radiations over a wide range are produced. Since $^{90}\text{Sr} - ^{90}\text{Y}$ beta source has endpoint energy of 2.28 MeV, it produces EB spectrum of continuous energy ranging from 0 to 2.28 MeV. This source of gamma radiation for photon energy in the range of our interest from 20 keV to 160 keV is used.

As the thickness of the nickel converter is less than the range of the beta particles, some of the energetic beta particles may get transmitted through the converter. These transmitted beta particles may produce unwanted EB photons in the detector. In order to prevent these beta particles from reaching the detector, a perspex absorber of 10 mm thickness is placed in between the converter foil and the detector.

The spectrum of these photons are recorded using an ORTEC make high resolution high purity Germanium (HPGe) detector of the type GMX 10P [136, 137]. This detector is coupled to an ORTEC type 8K multichannel analyzer (MCA) which has MAESTRO – 32 [138] software for data acquisition and analysis. The resolution of the detector was typically 600 eV at 5.9 keV.

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The background spectrum, the incident spectrum and the transmitted spectrum with an elemental target between the Perspex absorber and the detector, are recorded in succession. By making use of the background corrected incident and transmitted spectra the total cross section is determined for each elemental target in the energy range 20 – 160 keV. As the contribution due to elastic and inelastic scattering is found to be less than 3 %, hence the total cross section is due to the photoelectric absorption process only.

By measuring the background, incident and transmitted spectra, we have measured the various K shell photoelectric parameters and the real and imaginary parts of the anomalous scattering factors. The photoelectric cross section remains almost constant in the low energy region, shows a sudden increase at the K shell binding energy and again remains almost constant at high energies. Using the photoelectric cross section values at and around the K edge of the target atoms, various K shell photoelectric parameters and anomalous scattering factors are determined. The photoelectric cross sections at and around the narrow region of the K edge is used for determination of the K shell photoelectric parameters such as K shell photoelectric cross-section at K edge ($\tau_K$), K shell binding energy ($E_K$), K shell jump ratio ($r_K$), K shell jump factor ($J_K$), Davisson–Kirchner ratio, K shell oscillator strength ($g_K$) for all the elemental targets used in the present investigations. And the photoelectric cross section in the wide energy region of 30 to 110 keV is used to determine the real ($f'$) and imaginary ($f''$) part of the anomalous scattering factors of all the elemental targets of the present investigations. As we have measured the

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photoelectric cross section as a continuous function of energy across the K edge and fitted a well defined mathematical function, sigmoidal function, to the variation, we are able to determine more accurately the K shell photoelectric parameters.

Evidently the method adopted here is inexpensive and can be used to determine the photoelectric parameters and anomalous scattering factors for medium and high Z elements around the K and L shell absorption edges. By using a detector which has high energy resolution in the lower energy region this method can be extended to low Z elements also.

1.6. References


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