PREFACE.

The interaction of photons with matter has long been an important subject of investigation. This situation is due to continuing developments in theory and experimental technique of measurements. New theoretical developments on several photon interaction processes have been summarized among others by Hubbell (Hu 69, 73). The theoretical treatment of incoherent scattering of photons by atomic electrons (bound) for which an exact calculation, according to our information is not available, has much been improved through refined calculation of incoherent scattering function for complete exchange. Calculation of coherent Rayleigh scattering of photons by atoms has been improved through development of whole atom form factor calculations, considering relativistic effects. On the experimental side, the use of the newly developed experimental technique has lead to comparatively few experiments particularly on the incoherent scattering of photons by heavy atoms; although there are several early experiments using low Z elements like Carbon & Aluminium (atomic electrons assumed free) to verify the Klein-Nishina formula for the Compton effect. The situation in the case of coherent (elastic) scattering of photons of energy $\geqslant$ 1MeV, in high Z elements is not yet clear. Some discrepancy between the expected and the measured differential cross sections of 1.33 MeV photons at larger scattering angles has been observed (Dl70, Ha70, 71) and has remained unexplained.

The aim of the present set of measurements has been primarily to investigate the incoherent scattering of photons by low, intermediate and high Z atoms. Such measurements are judged to be useful in view of the present inadequacy in the experimental information and new theoretical developments. (Experimental verification of the theoretical prediction is as important as the theoretical developments.) The present investigation has been carried out using photons of energy near 1 MeV (because of their availability from BARC, India) by measuring the incoherent scattering function, the absolute differential cross section separately and the total scattering cross section. In course of these measurements, some data on the angular distribution of the coherently scattered photons have also been obtained and included in this thesis which is written in three chapters.

Chapter 1: A summary of developments in the theories of scattering of photons is given in this chapter. The development in the calculation of incoherent scattering function on the basis of Thomas-Fermi (TF), Hartree (H) and Hartree-Fock(HF) models has been briefly described and the results are compared. Recent calculation using SCF-HF wave functions extending over the relativistic range of momentum transfer has much been emphasized because of its better accuracy. Development in the calculation of atomic form factors from non-relativistic domain of momentum transfer in the TF model to the relativistic Dirac-Slater (DS) model & (HF) model has been briefly discussed. The exact calculation of Rayleigh scattering amplitudes from the individual electron shells of atoms at varying energy are not available as yet, except for only one set of data for K-shell of mercury at a few specified energies. For measurement with an arbitrary scatterer atom at a specified energy, exact shellwise Rayleigh scattering amplitudes, accurate real Delbrück amplitudes and the relative phases among these amplitudes are required to predict the theoretical angular distribution of scattering due to coherent sum of nuclear Thomson, Rayleigh and Delbrück amplitudes.

Chapter 2: Earlier experiments on whole atom incoherent scattering of photons have been summarised (Table 2.1). Most of these were carried out using single channel analyzer detection system by the auxiliary source method for the following reason. In a differential cross section measurement, the absolute incident beam intensity and the detector efficiency as a function of scattered photon energy must be known in addition to scattered intensity detected, the thickness of the scatterer and the effective solid angle between the detector and the scatterer. When the scattering is elastic, the counts from a weak source, placed in the position of the scatterer, of the same photon energy is compared with the detected scattered counts to determine the absolute differential scattering cross section. This procedure eliminates the individual measurement of absolute beam intensity and the detector efficiency and depends only on an accurate knowledge of the strength of the primary source in terms of that of the weak source. In the case of incoherent scattering, the scattered photon energy at each angle is different and the auxiliary source method can be applied only if the efficiency of detection is made independent of photon energy. Some authors (Si 63, Gh 65) have used a filter between the scatterer and the detector for obtaining the desirable type of detector system. It appears that in the differential type of measurement such a filter-detector assembly is not suitable for the following difficulties. (i) It is required that the detector, filter and the scatterer be widely separated so that the scattered photon from the scatterer enters the detector normal to its surface. This means a difficulty arising from poor statistics in scattered counts taken for a reasonably long interval of time.

(ii) The filter distorts the exact spectral shape of the scattered radiation. (iii) The filter imposes a certain lower energy limit below which the response drops.

Instead of using the auxiliary source method, we have compared the scattered counts at each angle from a given scatterer with those from a pure aluminium scatterer of radius exactly same as that of the scatterer. Since the energy of incoherently scattered photons by free electrons in aluminium is expected to be equal to that of photons scattered by loosely bound electrons in a heavy atom, the efficiency of detection in the two measurements taken consecutively at each angle is assumed to be the same. If measurements are carried out under the same experimental conditions with two scatterers of same size, the incident beam intensity, the efficiency factor and the effective solid angle cancel out in the determination of the ratio of differential cross section for a given atom to that for a free electron in aluminium. This ratio gives the value of incoherent scattering function.

The cylindrical scatterers chosen were as small in radius as practicable to minimise the effects of absorption and multiple scattering. For a sufficiently small scatterer thickness, the primary absorption factor is very small and the scattterering centres (the point sources of scattered radiation) can be assumed to be uniformly distributed. The correction for any absorption of the scattered radiation in the scatterer can be made using the self-absorption corrections for small gamma-ray source. The typical procedure of obtaining the results from the equation (2.5) using the measurements of photopeak count ratio is illustrated in tables 2.6 and 2.7. The spectram are taken with a multichannel analyser, using 512 channels. The figures 2.38 - 2.40 and tables 2.6 and 2.7 show a comparison of the spectral shapes and the results for slightly increasing scatterer radius. These results do not show any deviation within the experimental errors.

At smaller scattering angles, the measured count rate ratios at different scatterer radii could be extrapolated linearly (eqn.2.11) to zero scatterer radius and the cross section ratio could be determined. The small angle extrapolated results agree within about 6% with those given in the tables 2.8, 2.9 and 2.12.

The values of S determined in the angular range 10° - 165° for a number of elements (Cu, Sn, W, Hg, Pb) are shown in tables 2.8-2.12.

The absolute differential scattering cross section has also been measured by using the formula (eqn.2.12) of Quivy (Qu 66) based on absolute measurement of incident beam intensity and scattered intensity. This method requires the accurate values of the detector efficiency as a function of energy of the scattered photons. Since in the present measurements, the count in the photopeak part of the spectrum was taken, the intrinsic photopeak efficiency (product of total intrinsic efficiency and the peak-to-total ratio) was required. The total intrinsic efficiencies for the experimental geometries were calculated for the various scattered photon energies (table 2.4). The ratios of photopeak to total count were obtained experimentally in a few cases and also through interpolation of the accurate experimental data published recently (Mi 69).

Theoretical incoherent scattering functions and cross sections have been evaluated from Cromer's SCF-HF calculation data tabulated by Veigele et al (V 72). These theoretical S data along with our experimental data are plotted in figs.2.44 - 2.48 for interpretation as a function of $\frac{\sin \theta/2}{\lambda}\ \mathring{A}^{-1}$, although this is not an exact momentum transfer variable. The absolute cross sections are plotted in figs.2.50 - 2.52 for comparison with the corresponding theoretical values.

The earlier measurements covered only four elements for momentum transfer ranges as follows: Al and Cu upto $\frac{\sin \theta/2}{\lambda} = 2\ \mathring{A}^{-1}$ Fe upto $\frac{\sin \theta/2}{\lambda} = 35\ \mathring{A}^{-1}$ and Pb upto $\frac{\sin \theta/2}{\lambda} = 50\ \mathring{A}^{-1}$. The experimental errors in these measurements were large. The present set of data for five elements (Cu,Sn,W,Hg,Pb) covers a wide range upto $\frac{\sin \theta/2}{\lambda} = 89\ \mathring{A}^{-1}$, represents improvement in precision of measurements and appears to interpret in a satisfactory way the incoherent scattering process in low, intermediate and high Z atoms.

The measured spectra exhibit peaks in positions same as those due to unscattered 1.115 MeV photons. In some cases at angles in the range 30°-135° these elastic peaks were well resolved from the incoherent parts. From measurements with square cross section scatterers, where good spectra have been obtained, the differeutial cross sections for coherent scattering have been evaluated using the formula in equation 2.17. In absence of exact theoretical calculations of atomic Rayleigh amplitudes and Delbrück amplitudes at 1.115 MeV, our experimental results have been discussed with reference to a survey of earlier such data at the same energy.

Chapter 3: In an attempt to verify the incoherent scattering of photons completely, the total scattering cross sections have also been measured. In the energy region around 1 MeV, the incoherent scattering process is predominent over a wide range of Z from Z = 1 to about Z = 60. The coherent scattering cross section begins to affect the total scattering cross section above Z = 60. The minor contributions, which can be treated as corrections, from photoabsorption and pair production processes can be obtained from the newly available theoretical computations. Such accurate theoretical results were not available to the earlier workers who analysed their measured total cross sections. The present measurements of total attenuation of photons using the experimental arrangement shown in Fig.3.1 appear to represent improvement in the precision of some of the earlier such measurements. The systematic errors arising from small angle incoherent and coherent scatterings within the scattering cone of aperture θ_{max} (maximum value of θ in fig.3.7). The effect has almost been eliminated by making measurements at very small values of θ_{max} (20' - 27'). At this geometry the ratio of the number of scattered-in and that of transmitted photons for both coherent and incoherent scattering has been estimated and shown as an illustrative example in the table 3.9. Few measurements even at such small angle of scattering cone have been made at varying solid angles to determine whether there was any contribution from small angle scattering.

In some of the earlier measurements, thick attenuators have been used. In a thick absorber the multiple scattering is expected to affect the measurement of transmission ratio. In addition to using an extremely narrow beam collimation in the present work measurements for each element were carried out taking adequate precaution to minimise the effect of multiple scattering. For example, the direct spectral shape and the spectral shapes at varying absorber thickness were determined and the final measurements were taken at an absorber thickness giving the same resolution as from the direct spectrum.

The energy range was selected for the following reasons: First, around 1 MeV the incoherent scattering dominates over a wide range of Z. Second, at least six out of 34 elements measured have no data in this energy range; five elements have only one G.M.Counter data-point each at 1.25 MeV(mean energy of Co-60 1.173 and 1.332 MeV); at least two have only ion-chamber data. Finally, the gamma-ray sources used were the ones which were available locally at a comparatively low cost. In addition to these elements which have either no data or only GM/ion-chamber data in the energy range being considered, the present set of measurements include some seven elements for which no data have been available over the whole energy range from 100 eV to 10 MeV.

The statistical accuracy in the measurements were in the range 0.1 to 0.3 percent. Final error in total cross section which in some cases go upto 4 percent represent the combination of the statistical and other errors taken into consideration. The measured total scattering cross section data have been presented in tables 3.11 and graphs (3.8 - 3.22). In the graphs (3.8 - 3.12) our experimental data only for some selected elements along with newly available theoretical cross sections have been presented as a function of photon energy for comparison and interpretation. Most of these data do not overlap any earlier measured data for these elements.

In the second set of graphs, figs.3.13 - 3.22 our measured scattering cross sections and the corresponding Cromer's theoretical cross sections have been plotted as a function of atomic number Z for five photon energies . All these graphs taken together give a complete comparison of the plotted data and demonstrate closeness of agreement between the present data and Cromer's values.

The work described in this thesis was planned and started late in 1969. Although the results of initial measurements were published in different journals, it took a long time to complete the work owing to considerable delay in collecting the requisite apparatus and materials. The measurements that have been performed show that the incoherent scattering of photons in the energy range of the present work is well interpreted in terms of SCF-HF model calculations of incoherent scattering function.