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Compton scattering of 0·279 MeV gamma rays from K-shell electrons of lead

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Abstract. Differential cross-sections for Compton scattering of 0·279 MeV gamma rays from K-shell electrons of lead are measured at scattering angles ranging from 30 to 150° to study the effect of binding on the scattering process. Measurements are made employing two NaI(Tl) scintillation spectrometers and a slow-fast coincidence set-up of 30 nsec resolving time. The experimental results are compared with the available theoretical data. The total K-shell Compton scattering cross-section is 34% of the free electron Compton cross-section.

Keywords. Differential Compton cross-section; false coincidences; incoherent scattering function; x-ray-gamma ray coincidence.

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1. Introduction

Compton scattering of gamma rays is strongly affected by the binding of the scattering electrons. Early theoretical investigations are based on form-factor approximation and non-relativistic hydrogen-like wave functions. The general prediction of various calculations using different atomic models is that the scattered intensity becomes zero in the limit of vanishing energy or scattering angle and is given by the Klein-Nishina relation in the limit of infinite momentum transfer, broadened scattered spectra and Compton defect.

There have been a number of measurements (Spitale and Bloom 1977; Kane and Baba Prasad 1977; Nageswara Rao *et al* 1977; Murty *et al* 1977; Pradoux *et al* 1977; Swamy and Murty 1978; Acharya *et al* 1981; Ghumman *et al* 1981 and references therein) on Compton scattering of gamma rays from the K-shell electrons. Due to large uncertainties present in these measurements the agreement with each other and theory is only qualitative. We present experimental results of differential incoherent scattering cross-section of gamma rays from K-shell electrons of lead at scattering angles ranging from 30° to 150°.

2. Experimental set-up

When a gamma ray is scattered incoherently by an electron in the K-shell, the electron is ejected and a K x-ray is emitted. The probability of emission of the K x-ray is defined by the K-shell fluorescent yield of the scatterer atom. The measurement of the intensity of the scattered photon in coincidence with the K x-ray enables one to distinguish between the photons incoherently scattered by K-shell electrons and photons scattered by free or more loosely bound electrons.

The experimental arrangement used for the present measurements at 90° scattering angle is shown schematically in figure 1. A radioactive source of ^{203}Hg (neutron irradiated HgO) of initial strength 400 mCi is used to obtain 0·279 MeV gamma rays. Since this radioactive source decays with a half life of 46·8 days, several new sources are required on account of the long duration of the experiment. The scatterer foil is viewed by two detectors, one sensitive to characteristic x-rays and other to the scattered gamma rays. The scattered photons are detected by a 51 mm dia × 51 mm thick NaI(Tl) crystal and a 38 mm dia × 4 mm thick NaI(Tl) crystal is used to detect fluorescent K x-rays. The x-ray detector is placed at a distance of 120 mm from the scatterer centre and perpendicular to the scattering plane to minimize detector to detector scattering. The inside surface of the source collimator and all surfaces of the lead shielding viewing the scatterer and detectors are covered with a graded Z absorber of brass and aluminium with sufficient thickness to absorb 76·5 keV K x-rays emitted from the lead shielding. A slow-fast coincidence set-up using Canberra ARC timing amplifiers in the fast channels and of 30 nsec resolving time is used for recording the events. Lead scatterer (40 mm dia. and 30 mg/cm^2 thick) is used for the measurements.

Coincidence counts produced due to events in which the gamma detector receives a photon incoherently scattered by a K-shell electron at the same time as the x-detector receives the accompanying K x-ray, must be distinguished from accidental counts due to the finite resolving time of the coincidence circuit and coincidence counts produced by false events. The true coincidence count rate (N_c) is given by

$$N_c = N_t - N_{ch} - (N_f - N_{fch}),$$

where N_t is the total observed counting rate with the scatterer under investigation, N_{ch} is the accidental counting rate with scatterer in position, N_f is the false coincidence count rate and N_{fch} is the false accidental count rate.

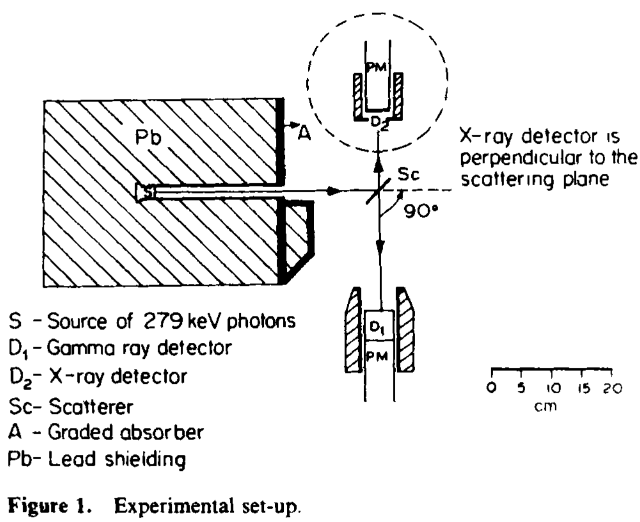

Figure 1. Experimental set-up.

False coincidences are produced due to the following events:

(i) Compton electrons can produce K x-rays by ionization during the slowing down process. These K x-rays may be detected in coincidence with the scattered gamma rays.

(ii) K-shell photoelectrons produce bremsstrahlung which may be recorded in the gamma detector in coincidence with the K x-rays.

(iii) The bremsstrahlung produced by Compton electrons during the slowing down process can be detected in coincidence with the gamma rays scattered from free electrons.

(iv) A gamma ray scattered incoherently by a K-shell electron but directed outside the gamma detector can be scattered into the detector by the surrounding material, producing a false coincidence.

(v) K-shell photoelectron ionizing the K-shell of some other atom, and this K x-ray may be detected by the gamma detector. This coincidence count rate is proportional to the square of the thickness t of the scatterer.

(vi) A low energy event produced by the scattered gamma ray in the x-ray detector can be detected in coincidence with the K x-ray detected in the gamma detector. This coincidence count rate is proportional to the thickness of the scatterer.

(vii) Coincidences may also be produced due to second order effects like double Compton scattering. This count rate is proportional to the thickness of the scatterer.

(viii) Coincidences due to detector to detector scattering.

(ix) Coincidence counts due to natural background, cosmic rays and weak radioactive source present in the laboratory.

(x) Coincidence counts due to the combination of the above process. This count rate is proportional to t^2 or higher powers of t.

The contribution of false coincidences due to events (v) and (vi) can be eliminated by biasing the gamma ray detector above the K x-ray peak. The false coincidences produced due to events (i), (ii), (iii) and (x) depend upon t^2 and can be reduced to a large extent by using a thin scatterer. False coincidences due to events (iv) and (viii) can be minimized by reducing the external material near the experimental set-up and by arranging a suitable shielding around the detectors in such a way that their field of view is confined to the scatterer only. The false coincidence count rate due to events (iii), (vii), (viii) and (ix) can be estimated experimentally (Shimizu *et al* 1965; Ghumman *et al* 1981) by replacing the scattering foil with some low Z material (aluminium) having the same number of electrons per cm^2 as the actual scatterer under investigation. All atomic electrons in aluminium can be considered to be free for incident energy of 0·279 MeV, as the binding energy for K and L shell electrons in aluminium is 1·6 keV and 0·08 keV respectively. As the aluminium scatterer is of low Z-value, the false coincidences due to bremsstrahlung may be different as compared to the false coincidences in the case of the actual target of lead, but East and Lewis (1969) and Kane and Baba Prasad (1977) have shown that this difference is rather insignificant.

Determination of the Compton scattering cross-sections from K-shell electrons requires an absolute measurement of the incident gamma ray flux at the scattering foil, the number of scatterer atoms per cm^2 and the detector efficiency. To avoid these measurements the bound electrons cross-section is determined relative to the cross-section due to free and stationary electrons which is given by the Klein-Nishina formula. For this purpose lead scatterer is replaced by an equivalent aluminium scatterer and the free electron Compton peak is recorded by the gamma ray detector.

3. Results and discussion

The experimental results for the differential cross-section ratio $d\sigma_K/d\sigma_F$ at various scattering angles for lead using 0·279 MeV gamma rays are shown in figure 2 along with other available data. An overall error of 15 to 25 % is involved in the determination of $d\sigma_K/d\sigma_F$ which includes counting statistics (10–20 %), scatterer thickness (< 1·5 %), fluorescent yield (2 %), self-absorption correction (2–3 %), detector efficiency (5 %) and measurement of solid angle (< 2 %). The representative coincidence count rates at three scattering angles with 30 mg/cm^2 thick lead scatterer are shown in table 1. At scattering angles of 30° and 150° used in the present measurements, the gamma ray detector is placed at a large distance from the scatterer centre to reduce the scattering effects from the collimator and background from lead shielding. This results in poor statistics at these angles. The window width of the x-ray channel was adjusted to accept 76·5 keV lead *K* x-rays. The gamma ray channel is adjusted to select gamma ray energies above lead *K* x-rays (100 keV) up to incident photon energy. Experimental results show that $d\sigma_K/d\sigma_F$ first increases to a maximum, passes through a broad minimum and then increases slightly. Small values of experimental results at small scattering angles is due to small momentum transfer to the struck electron compared with its initial momentum in the *K*-shell and hence the probability of ejection of an electron from its orbit is small.

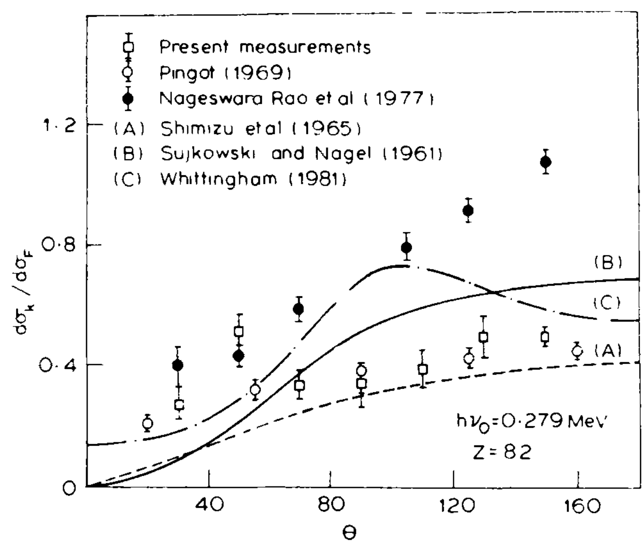

Figure 2. Differential Compton cross-section ratio $d\sigma_K/d\sigma_F$ at 0·279 MeV gamma rays for lead scatterer.

Table 1. Representative coincidence counts per 1000 sec at three scattering angles for lead scatterer of thickness 30 mg/cm^2.

θ	Distance of gamma-detector (mm)	N_t	N_{ch}	N_f	N_{fch}	N_c
30	400	7.15 ± 0.19	3.09 ± 0.13	3.43 ± 0.13	0.65 ± 0.06	1.28 ± 0.26
50	198	1.73 ± 0.08	0.21 ± 0.02	0.61 ± 0.04	0.05 ± 0.01	0.96 ± 0.096
110	148	1.70 ± 0.12	0.10 ± 0.03	0.89 ± 0.09	0.02 ± 0.01	0.73 ± 0.15

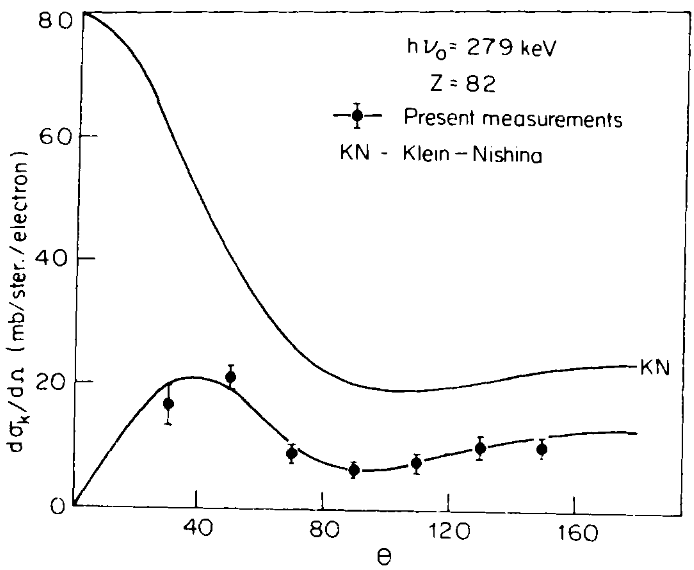

Figure 3. Angular variation of K-shell cross-section for lead and of Klein-Nishina cross-section at 0·279 MeV gamma rays.

Various theoretical investigations provide information on the Compton scattering cross-section for bound electrons which are based on different approximations. These theories are based on either form-factor approximation or incoherent scattering function approach. Shimizu *et al* (1965) obtained an expression for $d\sigma_K/d\sigma_F$ by using the initial wave function (non-relativistic) for K-shell in hydrogen-like atom and the final wave function by a plane wave. These results are shown by curve A and agree with our experimental results for scattering angles above 70°. Theoretical values of $S(h\nu_0, \theta, Z)$ obtained from the data given by Sujkowski and Nagel (1961) are shown by curve B. Relativistic calculation of Whittingham (1981) are shown by curve C, indicating a broad maxima around 100°. Our experimental results also show a maxima but at a relatively smaller scattering angle of 50°. The phenomenon of peak structure is supported by non-relativistic calculations of Tseng *et al* (1973), relativistic calculations of Wittwer (1972; Sn and Au at 145 keV and Au at 320 keV), Pradoux *et al* (1977; Ge at

662 keV) and experimentally by Kane and Baba Prasad (1977; Au and Th at 1·12 MeV) and Pradoux *et al* (1977; Ge at 662 keV).

There is no experimental data at 0·279 MeV gamma rays for lead scatterer. We have compared our experimental data with the experimental results of Pingot (1969) for gold ($Z = 79$) and that of Nageswara Rao *et al* (1977) for bismuth ($Z = 83$) which have Z-values close to our lead scatterer. At scattering angles above 50°, our experimental results agree with the data of Pingot (1969) within experimental error, but are smaller than the corresponding values of Nageswara Rao *et al* (1977).

The value of the K-shell Compton scattering cross-section ($d\sigma_K/d\Omega$) is obtained from the experimental results by using the well established Klein-Nishina cross-section ($d\sigma_F/d\Omega$) and is shown in figure 3. The total K-shell Compton scattering cross-section is obtained by integrating the values of $d\sigma_K/d\Omega$. For this purpose the experimental curve for angular variation of K-shell Compton scattering cross-section is extrapolated to 180° on the higher angle side and to zero value of the cross-section at zero scattering angle as shown in figure 3. The total K-shell scattering cross-section is 0·34 σ_F for lead, where σ_F is the total Klein-Nishina cross-section.

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