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COLLISION INTEGRAL CROSS SECTION MEASUREMENTS IN TWO-PHOTON COMPTON SCATTERING

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The collision integral cross sections in two-photon Compton scattering are measured experimentally for 0.662 MeV incident gamma photons. Two simultaneously emitted gamma quanta are investigated using a slow-fast coincidence technique of 25 ns resolving time. The coincidence spectra for different energy windows of one of the two final photons are recorded using HPGe detector. The experimental data do not suffer from inherent energy resolution of gamma detector and provide more faithful reproduction of the distribution under the full energy peak of recorded coincidence spectra. The present results of collision integral cross sections are in agreement with the currently acceptable theory of this higher order process.

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1. Introduction

The interaction of a gamma photon with an electron may result in a final state consisting of two or more photons at the same time as the recoil electron. These multi-photon processes are typical quantum electrodynamics (QED) effects and the probability of their occurrence increases with increase in incident photon energy. The two-photon Compton scattering is the dominant process of all succeeding processes of multi-photon Compton scattering. In this higher order QED process the collision products are two simultaneous degraded gamma quanta along with recoil electron. Heitler and Nordheim [1] postulated the existence of this phenomenon and calculated order of magnitude of cross section in restrictive conditions, unfavourable for experimental verification. Eliezer [2] set up an expression for collision

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differential cross section of this process in the limiting case of one hard and one soft photon only. Mandl and Skyrme [3] using S-matrix formalism of quantum electrodynamics have provided an exact theory of this process. Their expression for the collision differential cross section can be regarded as two-photon Compton analog of the well-known Klein–Nishina relation for single-photon Compton scattering.

Two-photon Compton scattering is important because:

(i) It is a major background process in the experimental study of another non-linear QED process namely photon splitting in field of heavy atoms, the first experimental confirmation of which has recently been reported by Akhmadaliev *et al.* [4].

(ii) It provides a test of quantum electrodynamics (QED) in an implicit way, although QED has been tested too much higher accuracy.

(iii) It provides a mechanism of photon multiplication [5] in astrophysics.

(iv) This effect contributes appreciably to total scattering coefficients at higher incident photon energies.

Energy spectra and collision cross sections integrated over energy of one of the two final photons are reported in measurements [6]. These measurements correspond to two different sets of geometry. One in which one of the two final photons is detected at 70° to the incident beam and the other being detected at 90° with the angle between them being 90°, and the second geometry differing from the first one that one of the emitted final photon being detected at 100° instead of 70°. More recently our group has reported measurements [7] for collision, scattering and absorption differential cross sections of this process. Many systematic effects contributing to true events have been taken into account. The limitations suffered by various experiments reported in literature are also described therein. The incident photon energy in measurements [6, 7] being 0.662 MeV and thin aluminium foils is used as scatterer. The measured results agree with theory within experimental estimated error. These measurements suffer from poor energy resolution of scintillation spectrometers. Measurement [8] provides interdependence of energy between the two final photons emitted in this process and confirms continuous nature of energy spectra for the emitted photons. In these measurements [8], coincidence spectra are recorded using HPGe detector and the data on energy distribution do not suffer from the energy resolution of the gamma detector but are confined to interdependence of energy between the two final photons of this process.

In the present work, the collision cross sections integrated over energy are measured by recording energy spectra of one of the two final photons using HPGe detector for the geometry when one of the two final photons is detected at 50° and the other at 90° to the incident beam with angle between them being 90°. The present geometry is chosen because no data on collision integral cross section for different energy windows of one of the two final photons are available in the forward hemisphere except at scattering angle of 70°. The present data support the collision cross section formula provided by Mandl and Skyrme [3] and do not suffer from inherent energy resolution of gamma detector.

2. Experimental set-up

The principle of present measurements is based upon detection of two simultaneously emitted gamma quanta in this process using two gamma ray spectrometers working in coincidence. Figure 1 shows details of source and detectors shielding. A cylindrical beam collimator consisting of a brass pipe and fitted with aluminium windows on both ends can be filled with a column of mercury between measurements and is used to open and close the incident beam. The conical lead collimator reduces effect of scattering from edges.

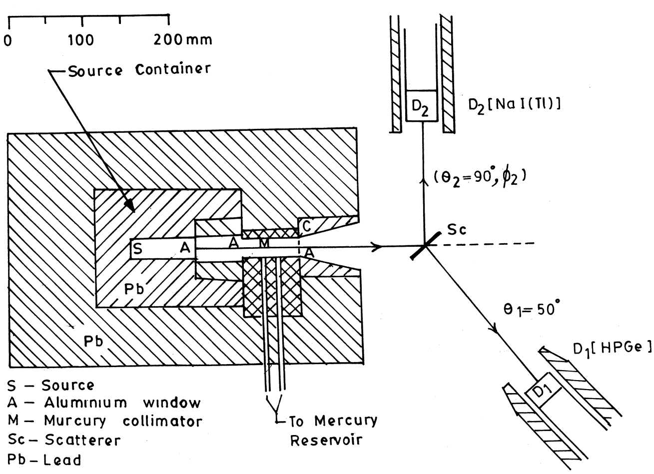

Fig. 1. Experimental set-up, S: 8 Ci ^{137}Cs radioactive source; Sc: Aluminium scatterer; D_1: HPGe detector of dimensions 56.4^{ϕ} mm $\times$ 29.5 mm; D_2: NaI(Tl) scintillation detectors of dimensions 51^{ϕ} mm $\times$ 51 mm; Pb: Lead shielding.

An intense beam of gamma rays from an 8 Ci ^{137}Cs radioactive source is made to fall on a thin aluminium target of thickness 17.48 mg cm^{-2}. Two gamma detectors detect the two gamma quanta emitted simultaneously in this process. The detector D_1, an HPGe detector (of dimensions 56.4^{ϕ} mm $\times$ 29.5 mm) and the detector D_2, a NaI(Tl) detector (of dimensions 51^{ϕ} mm $\times$ 51 mm) are placed at 50° and 90° to the incident beam respectively, with the angle between them being 90°. The detector assemblies are arranged in such a way that the axes of two gamma detectors and source collimator pass through center of scatterer. The detectors are properly shielded by cylindrical lead shielding and inner side of each shielding is covered with 2 mm thick iron and 1 mm thick aluminium, with iron facing lead to absorb K X-rays emitted by lead shielding. The faces of both detectors are also placed well inside the cylindrical lead shielding to prevent photons scattered from face of one detector from reaching the other. The positions of both detectors are adjusted in such a way that they do not view the source window directly. Further shielding of detectors produce no change in the coincidence count rate, indicating that cross scattering is negligible. For the present measurements, the solid angles subtended by the two detectors at scattering centre are 0.24% and 0.45% respectively, thus variation of scattering angles about median rays in direction of the detectors are limited to $\pm 5.6°$ and $\pm 7.6°$ respectively. These variations are quite small in comparison to 34° spread in measurement [9]. A timing electronics using Canberra ARC timing amplifiers and of 25 ns resolving time is used to record these events.

The photopeak efficiency curves for both the detectors are shown in Fig. 2. The curve for NaI(Tl) scintillation detector is obtained from data for intrinsic efficiency and photofraction reported by Crouthamel [10], and corrected for iodine escape peak [11, 12] and absorption in aluminium windows [13]. The efficiency curve for HPGe detector is provided by Canberra

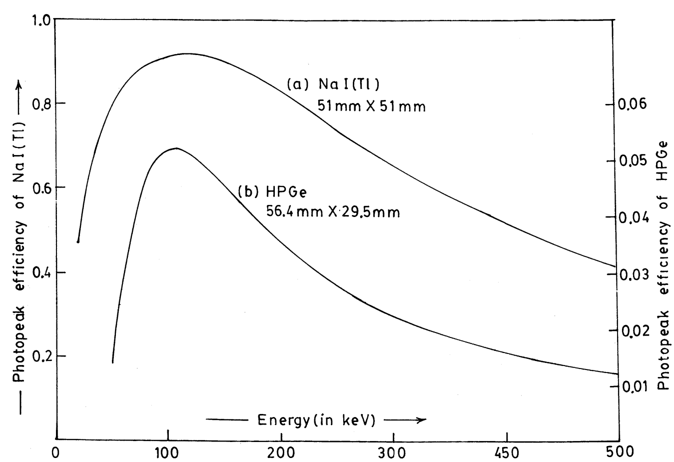

Fig. 2. Photopeak efficiency of NaI(Tl) scintillation detector (curve (a) and scale along left y-axis) and HPGe detector (curve (b) and scale along right y-axis).

Germanium detector user's manual [14]. The experimental measured values of photopeak efficiency of both detectors using single energy sources of ^{137}Cs and ^{203}Hg of known source strengths are nearly in agreement with theoretical values.

3. Method of measurements

In the present measurements, we have recorded coincidence spectrum of one of the emitted photons, having energy E_1, by fixing energy window of the second photon, of energy E_2, on PC-based MCA, which is gated with output of the coincidence set-up. Both the detectors are biased above K X-ray energy of the scatterer (1.56 keV for aluminium scatterer). The coincidence count rates are recorded with and without aluminium scatterer in the primary incident gamma beam. The registered coincidences with aluminium scatterer in the primary beam correspond to true events due to two-photon Compton scattering, chance and false events. The registered coincidences without aluminium target in primary beam are due to cosmic rays and to any other process independent of target, and thus account for false coincidence events. The chance coincidence count rates in these measurements are also recorded by introducing a suitable delay in one of the detecting channels. The true coincidence spectrum due to two-photon Compton scattering events is obtained by subtracting the contribution of target-out and chance coincidences from the observed target-in coincidences. As the probability of occurrence of this process is quite small, the experiment is run over a long period of time (nearly one month for each energy window) to achieve reasonable counting statistics. The calibration and stability of the system are checked regularly and adjustments are made if required.

The number of coincidences registered per unit time, N_d, from two-photon Compton scattering events, in which one of the two final photons having energy window ΔE_1, is scattered into an element of solid angle $d\Omega_1$, in direction of the HPGe detector and the second photon having energy window ΔE_2 being scattered into an element of solid angle $d\Omega_2$ in direction of NaI(Tl) scintillation detector, are given by

$$N_d = I_0 n_e t \left(\frac{d^2\sigma_D}{d\Omega_1 d\Omega_2}\right)_{\Delta E_2} d\Omega_1 \varepsilon_1 \left(\Delta E_1\right) d\Omega_2 \varepsilon_2 \left(\Delta E_2\right) , \tag{1}$$

where I_0 being incident flux at the scatterer, n_e is electron concentration in the target having thickness t, $\varepsilon_1(\Delta E_1)$ and $\varepsilon_2(\Delta E_2)$ are the averaged photopeak efficiencies of HPGe and NaI(Tl) scintillation detectors for above defined energy windows of the two final photon respectively, and $(d^2\sigma_D/d\Omega_1 d\Omega_2)_{\Delta E_2}$ is the probability for two-photon Compton process to occur with ΔE_2 being independent energy window. The lower limit of energy window for one of the two final photons determines the upper limit of energy window of other photon and vice versa, according to the following equation in the present geometry:

$$E_1 = \frac{m_0 c^2 E_0 - E_2(m_0 c^2 + E_0)}{m_0 c^2 + E_0[1 - \cos\frac{5\pi}{18}] - E_2}\,, \tag{2}$$

with $m_0 c^2$ being electron's rest mass energy.

To avoid measurements of quantities like incident flux at the scatterer, electronic concentration in scatterer, scatterer thickness *etc.*, two-photon Compton cross sections are measured relative to single-photon Compton scattering. The number of gamma photons scattered per unit time, N_s, by free electrons through single-photon Compton scattering events under the same experimental conditions as described above and detected by HPGe detector, are given by

$$N_s = I_0 n_e t \left\langle \frac{d\sigma_{\mathrm{KN}}}{d\Omega_1} \right\rangle d\Omega_1 \varepsilon_1' \left(E_1'\right)\,, \tag{3}$$

where $\varepsilon_1'(E_1')$ being efficiency of HPGe detector corresponding to single-photon Compton scattered energy E_1' in direction of the detector and $\langle d\sigma_{\mathrm{KN}}/d\Omega_1\rangle$ is Klein–Nishina cross section for single-photon Compton scattering averaged over the solid angle subtended by HPGe detector.

Using Eqs. (1) and (3), the two-photon Compton cross section is given by

$$\left(\frac{d^2\sigma_D}{d\Omega_1 d\Omega_2}\right)_{\Delta E_2} = \frac{N_d}{N_s}\left\langle \frac{d\sigma_{\mathrm{KN}}}{d\Omega_1}\right\rangle \frac{\varepsilon_1'\left(E_1'\right)}{\varepsilon_1\left(\Delta E_1\right) d\Omega_2 \varepsilon_2\left(\Delta E_2\right)}\,. \tag{4}$$

The quantities such as N_d and N_s are measured experimentally. The solid angles are measured from geometry of the experimental set-up. Single-photon Compton cross sections are calculated from Klein–Nishina relation and photopeak efficiency of gamma detectors is provided by curves of Fig. 2.

4. Results and discussions

In the present measurements, four different energy intervals of E_2 have been selected and corresponding energy spectra of E_1 are recorded. The full energy peaks (superimposed in single spectrum) of coincidence spectra, corrected for false and chance events, of one of the two final photons, E_1, for different energy windows of the other photon are shown in Fig. 3. The solid curve in each of the full energy peak represents the best-fit curve through experimental points corresponding to the peak observed in energy spectrum.

The improved energy resolution leads to a more faithful reproduction of the shape of distribution under the full energy peak for each energy window of E_2. It is obvious that the main part of contribution to energy spread in observed full energy peak in the present experimental arrangement is caused by finite energy window of the other detector and not the intrinsic resolution of the spectrometer, as suggested in earlier works [6,7,9,15] on this subject. The contribution to energy spread due to angular aperture of the spectrometer and finite thickness of the scatterer is negligible in comparison to finite energy window's contribution. It has been seen that the shift in energy corresponding to the peaks observed in different energy spectra for different target thickness is within experimental estimated error of nearly 1.0%. The full energy peak in the coincidence spectra corresponding to energy windows of 50–125 keV and 225–275 keV are not symmetrical about their respective peak positions. This behavior is because of the fact that two-photon Compton process is more probable with the emission of one hard and one soft photon rather than two photons of approximately equal energy. The observed coincidence count rate under the peak of recorded energy

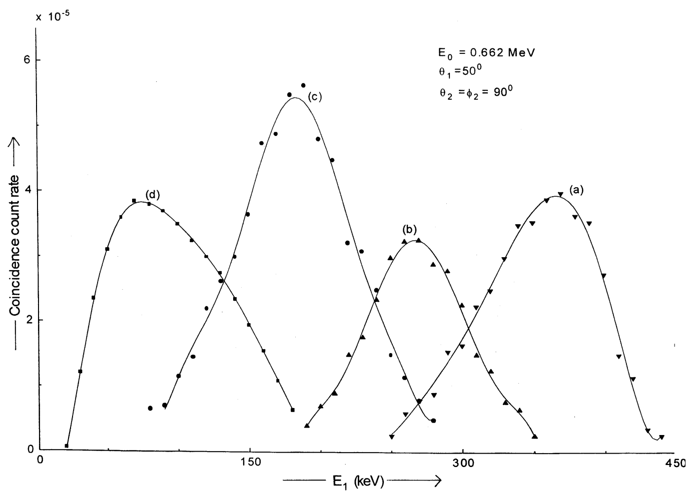

Fig. 3. Spectral distribution of E_1 (full energy peaks only) of different energy spectra superimposed in a single spectrum corresponding to different energy windows of the second photon (E_2). The full energy peaks correspond to $\Delta E_2 = 50$–100 keV (curve (a)), 125–175 keV (curve (b)), 175–225 keV (curve (c)) and 225–275 keV (curve (d)), respectively.

spectrum consists of coincidences resulting from interactions in the target. These coincidences correspond to two-photon Compton (TPC) scattering and Compton-bremsstrahlung (CB) events. The CB background, amounting on the average to about 3.58% of the TPC count rate for $\cong 18\ \mathrm{mg\,cm^{-2}}$ target thickness, is eliminated on the basis of an experimental approach suggested in our previous measurements [15]. For the present measurements, the selected energy window of E_2 (175–225 keV) and experimentally observed spread of E_1 (142–232 keV) overlap, and the observed coincidence counting rate is corrected for this particular case according to the relation

$$(N_d)_{\text{corrected}} = \frac{(N_d)_{\text{observed}}}{1+f} \tag{5}$$

with f being the degree of overlapping and for this specific energy window the value of f being 0.56. The integral cross section value for this specific energy window is evaluated after correcting the observed coincidence count rate.

The collision integral cross sections for two-photon Compton scattering for different energy windows of the second photon are calculated from the coincidence count rate due to two-photon Compton scattering, single-photon Compton scattering count rate and other required parameters. The coincidence count rates resulting from purely two-photon Compton scattering events (after elimination of CB-events and corrected for overlapping of energy windows if any) are given in column 2 of Table I. Column 3 of the table provides count rate resulting from single-photon Compton scattering recorded by HPGe detector. The measured values of the collision integral cross section are given in column 4 of Table I. Column 5 gives the corresponding values calculated from theory for the same energy window and direction of emission of the resulting gamma quanta. The errors indicate statistical uncertainties only. The measured value of two-photon Compton integral cross section with independent energy interval of E_2 from 50–275 keV comes out to be $(3.57 \pm 0.32) \times 10^{-30}\mathrm{cm^2sr^{-2}}$ and is lower than the corresponding value of $4.78 \times 10^{-30}\mathrm{cm^2sr^{-2}}$ deduced from theory [3]. The presently measured values of collision integral cross section, although of same magnitude, show deviation from the corresponding theoretical values and no positive reason could be assigned for these deviations.

An overall error of nearly 11–19% is estimated in the present measurements and is due to statistical uncertainties in the coincidence count rate due to two-photon Compton scattering events, single-photon Compton count rate, solid angles, detector efficiencies and scatterer thickness. The error in the measurement of various quantities is given in Table II. The maximum uncertainty in the measurement of energy is estimated to be less than 1.0%. The self-absorption in the target is estimated to be less than 1% for energies greater than 30 keV. The probability of photons being split by the nuclear electrostatic field [16] is negligible. The efficiency of the fast coincidence set-up is 100%. The detector to detector scattering contribution to coincidences is almost negligible.

TABLE I

Present measured results of collision integral cross sections in two-photon Compton scattering for 0.662 MeV incident gamma photons for the geometry $\Theta_1 = 50°$, $\Theta_2 = 90°$ and $\Phi_2 = 90°$. The errors indicate statistical uncertainties only.

ΔE_2 (in keV)	N_d (per Ksec)	N_s (per sec)	Collision integral cross section $\times 10^{-30}\mathrm{cm}^2\mathrm{sr}^{-2}$	
			Exptl.	Theory*
50–125	0.318 ± 0.029	113.2 ± 0.6	1.17 ± 0.11	1.56
125–175	0.174 ± 0.029		0.45 ± 0.08	0.52
175–225	0.328 ± 0.025		0.70 ± 0.05	0.65
225–275	0.771 ± 0.048		1.25 ± 0.08	2.05

*Values calculated from theory [3].

TABLE II

Error involved in the measurement of various quantities.

Quantity	Nature of uncertainty	Uncertainty (%)
Measurement of N_d	Statistical	~ 7.0–16.7
Measurement of N_s	Statistical	< 1.0
Solid angles	Systematic	~ 1.8
Scatterer thickness	Systematic	~ 1.2
Detector efficiency	Systematic	~ 5.0
Energy	Systematic	< 1.0

Since the theoretical cross section varies over the angles allowed by the two detector apertures and finite energy window of independent final photon energy, the averaged theoretical cross section values are obtained from the following equation by numerical integration.

$$\left(\frac{d^2\sigma_D^{\mathrm{th}}\,(\varDelta E_2)}{d\varOmega_1 d\varOmega_2}\right)_{\mathrm{av}} = \frac{1}{\varOmega_1\varOmega_2}\int\limits_{\varOmega_1}\int\limits_{\varOmega_2}\left(\frac{d^2\sigma_D^{\mathrm{th}}\,(\varDelta E_2)}{d\varOmega_1 d\varOmega_2}\right) d\varOmega_1 d\varOmega_2 \tag{6}$$

with $\varDelta E_2$ being independent final photon energy window. The maximum deviation of the average cross-section values from the unaveraged one is found to be less than 2.0% where as in measurements [9] these values differ by more than 10%.

Our results for two-photon Compton scattering support the theoretical differential cross section formula for this weak order process, derived by Mandl and Skyrme [3]. The present measurements also confirm that the probability for occurrence of this process is quite small as compared to that of single-photon Compton scattering. Here it is also important to note that attempts on this objective have been very rare. So our present findings will serve very good reference for further comparison with experimental data of this process. Our understanding of this process is certainly incomplete and the experimental data on this higher order process are confined to 0.662 MeV incident photons and needs further investigations at higher incident photon energies where this higher order process is more likely to occur. A more faithful reproduction of the shape of distribution under the full energy peak favours the use of HPGe detector and contrary to this the intensity measurements discourage the use because of its low efficiency. No doubt the experiment requires long periods of exceptional stability, because the coincidence count rates are extremely small, but an extensive experimental study of this process will help in the investigation of photon splitting in the electric field of heavy atoms, the first successful experimental confirmation of which has been carried by Akhmadaleiv *et al.* [4] at Budhker Institute of Nuclear Physics (Novosibirsk, Russia).

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