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Measurement of two-photon production cross sections resulting from photon-electron collisions

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Abstract : The collision integral cross sections for production of two final state photons originating from photon-electron collisions 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 the present results of collision integral cross sections are in agreement with theory.

Keywords : Two-photon Compton scattering, collision integral cross sections, coincidence events.

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1. Introduction

The quantum electrodynamic (QED) process in which interaction of an incident photon with an electron gives rise to emission of two simultaneously degraded gamma quanta at the same time as the recoil electron is known as two-photon Compton scattering. Mandl and Skyrme [1] using *S*-matrix formalism of QED have provided an exact theory for this process. The probability of occurrence of this process increases with increase in incident photon energy. There is a renewed interest in the experimental studies of this process because it is a major background process in the study of photon splitting in the electric field of heavy atoms, the first experimental confirmation of which has recently been reported by Akhmadaliev *et al* [2]. The significant background process contributing to the registered events is from two-photon Compton scattering of the incident photons by the atomic electrons ($\gamma_0 + e \rightarrow \gamma_1 + \gamma_2 + e$).

The collision cross sections integrated over energy of one of the two final photons emitted in this process are reported in our earlier measurements [3]. 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 is that one of the final photons being detected at 100° instead of 70°. More recently, our group has reported measurements [4] for collision, scattering and absorption differential cross sections of this process. The limitations suffered by various experiments reported on this process are also described therein. The incident photon energy in measurements [3,4] being 0.662 MeV and these measurements suffer from poor energy resolution of the scintillation spectrometers.

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 emitted photons is detected at 50° and the other at 90° to the incident beam with angle between them being 180°. The present geometry is chosen because no experimental data on collision integral cross sections are available in the forward hemisphere except at a scattering angle of 70°. The present experimental data do not suffer from inherent energy resolution of gamma detector and support the collision cross section formula provided by Mandl and Skyrme [1].

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2. Experimental set-up and method of measurement

Figure 1 shows the experimental arrangement used for the present measurements and its details are given elsewhere [4]. An intense beam of gamma rays from an 8 Ci ^{137}Cs

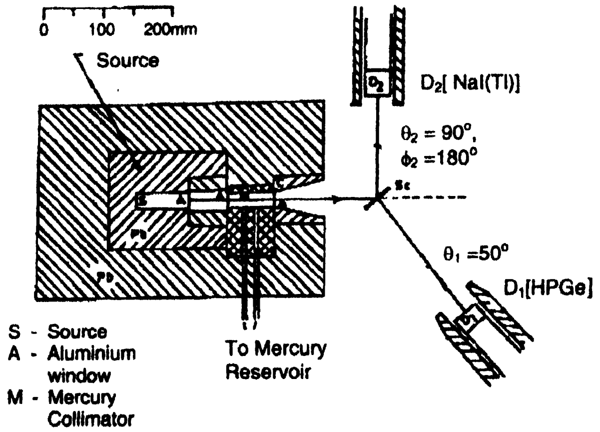

Figure 1. Experimental set-up, S : 8 Ci ^{137}Cs radioactive source; Sc : Aluminium scatterer; D_1 : HPGe detector of dimensions 56.4$^\phi$mm × 29.5 mm; D_2 : NaI(Tl) scintillation detectors of dimensions 51$^\phi$mm × 51 mm; Pb : Lead shielding.

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$^\phi$ mm × 29.5 mm) and the detector D_2, a NaI(Tl) detector (of dimensions 51$^\phi$ mm × 51 mm) are placed at 50° and 90° to the incident beam respectively, with the angle between them being 180°. The detector assemblies are arranged in such a way that the axes of two gamma detectors and source collimator pass through the centre 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 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. 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 ±5.5° and ±5.2° respectively. A timing electronics using Canberra ARC timing amplifiers and of 25 ns resolving time is used to record these events.

In the present measurements, the coincidence spectra 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 two-photon Compton collision integral cross section is given by

$$\left.\frac{d^2\sigma_D}{d\Omega_1 d\Omega_2}\right)_{\Delta E_2} = \frac{N_d}{N_s}\left\langle\frac{d\sigma_{KN}}{d\Omega_1}\right\rangle \frac{\varepsilon_1'(E_1')}{\varepsilon_1(\Delta E_1)\,d\Omega_2\,\varepsilon_2(\Delta E_2)} \tag{1}$$

where N_d is true coincidence count rate due to two-photon Compton scattering events; N_s is the single-photon Compton scattering count rate for the detector D_1; Ω_1 and Ω_2 are solid angles subtended by the two detectors at the scattering centre; $\langle d\sigma_{KN}/d\Omega_1\rangle$ is the Klein-Nishina cross section for single-photon Compton scattering in the direction of detector D_1 and averaged over the subtended solid angle; $\varepsilon_1(\Delta E_1)$ and $\varepsilon_2(\Delta E_2)$ are the efficiencies of the two detectors for two emitted gamma photons having energy windows ΔE_1 and ΔE_2 respectively, and $\varepsilon_1'(E_1')$ is the efficiency of detector D_1 corresponding to energy E_1' due to single-photon Compton scattering in the direction of the detector.

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 detector efficiencies are calculated from the available literature.

3. Measurements in coincidence

In addition to coincidence events recorded due to two-photon Compton scattering, the following are the main sources of false events under the present experimental conditions :

(i) The bremsstrahlung produced by recoil Compton electrons may be detected in coincidence with single-photon Compton scattered gamma rays.

(ii) Detector to detector scattering may also contribute to false coincidences.

(iii) The natural background, cosmic rays and weak radioactive sources present in the laboratory.

(iv) Two-photon Compton scattering events taking place from air and other surrounding materials may also contribute to coincidences.

(v) Higher order processes like three-photon Compton scattering may also contribute to coincidences.

The contribution due to events (ii) is minimised by proper shielding of the two detectors and keeping their faces well inside the lead shielding so that the photons scattered from the face of one detector may not reach the other detector. The contributions due to events (iii) and (iv) are measured experimentally by recording the coincidence count rate without aluminium scatterer in the primary beam. The contribution due to event (v) is negligible, as the cross section for this process is α (Fine structure constant $\cong 1/137$) times than for two-photon Compton scattering. The elimination of coincidences due to event (i) is carried out experimentally.

In the present measurements, we have recorded coincidence spectrum of one of the emitted photons having energy E_1, by fixing the energy window of the second photon of energy E_2, on a PC-based MCA, which is gated with the output of the coincidence set-up. Both the detectors are biased above the K X-ray energy of the scatterer (1.56 keV for aluminium scatterer). Experimental measurements are made as follows :

(i) The coincidence energy spectra of E_1, for a finite energy window of E_2, are recorded with the aluminium scatterer in the primary beam.

(ii) The chance (or random) count rates in the above measurements are recorded by introducing a suitable delay of 75 ns in one of the detecting channels. Introducing this delay eliminates true coincidences corresponding to the processes in which two correlated gamma rays are detected in coincidence.

(iii) Coincidences are recorded after removing the aluminium target out of the primary beam to permit registration of the coincidences due to cosmic rays and to any other process independent of the target.

(iv) Chance coincidences in measurement (iii) are recorded as described in (ii).

(v) The single-photon Compton spectra for both the detectors are recorded with the same aluminium scatterer in the primary beam.

Measurements under condition (i) to (v) are recorded in alternative time intervals with a view of avoiding errors due to possible effect of any drift in the system during measurements, which takes nearly a month for one finite energy window of E_2. 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. Since true coincidences are few in number, the experiment is performed over a long period of time to achieve reasonable counting statistics. The calibration and stability of the system are checked regularly and adjustments are made, if required.

The resolving time of the coincidence set-up is obtained from observed coincidence count rate under condition (ii) and individual count rates N_1 and N_2 of the two gamma detectors using the relation

$$N_{ch} = 2\tau_0 \, N_1 \, N_2 , \qquad (2)$$

where $2\tau_0$ is the resolving time of the electronic set-up and in the present measurements comes to be 25 ns.

Efficiency of the coincidence set-up is measured experimentally using ^{22}Na radioactive source. Both gamma detectors subtending equal solid angles are placed exactly opposite to each other. The coincidence count rate is found to be exactly in agreement with the individual count rate of one of the detectors (HPGe for the present experimental setup).

4. Results and discussion

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 Figure 2. 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 the 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 [3–6] on this subject. The full energy peak

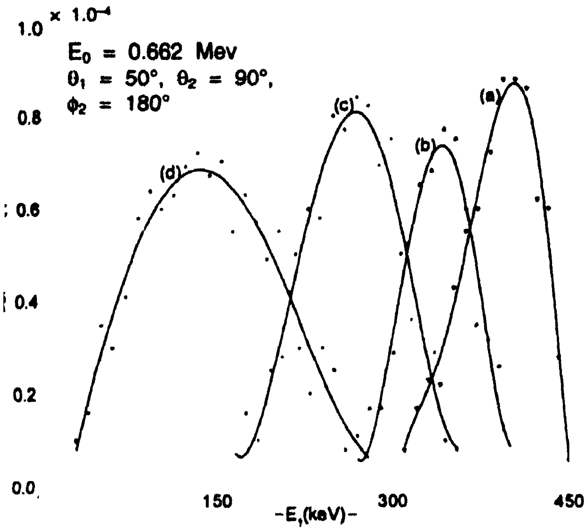

Figure 2. Spectral distribution of E_1 (full energy peaks only) of different energy spectra superimposed in a single spectrum corresponding to different energy windows of the second photon (E_2). The full energy peaks correspond to ΔE_2 = 50–125 keV (curve-a), 125–175 keV (curve-b), 175–225 keV (curve-c) and 225–275 keV (curve-d) respectively.

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 behaviour 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 collision Integral cross sections for two-photon Compton scattering for different energy windows of the second photon are calculated from the coincidence count rates due to single-photon and two-photon Compton scattering, and other required parameters. Here, the selected energy window of E_2 (175-225 keV) and experimentally observed spread of E_1 (212-303 keV) overlap (overlapping being 0.14%), the observed coincidence counting rate is corrected as reported in measurements [4].

The coincidence count rates resulting from purely two-photon Compton scattering events (after elimination of CB-events, amounting on the average to about 3.58% of the two-photon Compton count rate for ≅18 mg-cm^{-2} target thickness) are given in column 2 of Table 1. 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 1. 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

Table 1. 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 $\phi_2 = 180°$. The errors indicate statistical uncertainties only.

ΔE_2 (in keV)	N_d (per ks)	N_s (per sec)	Collision integral cross section $\times 10^{-30}$ cm^2 sr^{-2} Exptl.	Theory
50–125	0.51 ± 0.08	111.1 ± 0.6	4.36 ± 0.68	5.38
125–175	0.18 ± 0.03		1.34 ± 0.22	1.24
175–225	0.45 ± 0.07		2.49 ± 0.38	0.89
225–275	0.99 ± 0.17		3.57 ± 0.61	1.63

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 (1.17 ± 0.11) × 10^{-29} cm^2 sr^{-2} and is slightly higher than the corresponding value of 0.91 × 10^{-29} cm^2 sr^{-2} deduced from theory [1]. The presently measured values of collision integral cross section, although of same magnitude, show deviation from the corresponding values obtained from theory [1], and no positive reason could be assigned for these deviations.

An overall error of nearly 18% is estimated in the present measurements which is due to statistical uncertainties in the coincidence count rates for the single-photon (<1.0%) and two-photon (~16%) Compton scattering events, solid angles (~1.8%), detector efficiencies (~5.0%) and scatterer thickness (~1.2%). The self-absorption in the target is estimated to be less than 1% for energies greater than 30 keV. The efficiency of the fast coincidence set-up is 100%. The detector to detector scattering contribution to coincidences is almost negligible.

Our results support the theoretical differential cross section formula for this higher order process, derived by Mandl and Skyrme [1]. 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 as a very good reference for further comparison with experimental data of this process. 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. 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 observation of which has been carried by Akhmadaliev *et al* [2] at Budhker Institute of Nuclear Physics (Novosibrisk, Russia).

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