Chapter III

OVERVIEW OF THE INSTRUMENT BACKGROUND

Although the requirement of two separate interactions for Compton telescopes greatly reduces the background contribution to the measured count rate, it simultaneously reduces the overall detection efficiency. To compensate for the reduced efficiency, Compton telescopes are generally large and massive, both in terms of their stopping power required in the detector system as well as in their shields. The intimate relationship between the medium energy gamma rays and nuclear de-excitations ensures that the telescope itself becomes a bright source of background, especially when it operates in regions of intense high-energy particle fluxes. The background experienced by COMPTEL is therefore both intense and complex in its origin. This is the case for any gamma ray detector that operates in low-Earth orbit since it is exposed to a high intensity of primary cosmic-ray particles and other secondary particles. Consequently, COMPTEL normally operates under conditions of intrinsically low signal-to-background ratio (except perhaps for transient phenomenon like GRBs and solar-flares).

The cosmic diffuse gamma (CDG) radiation is assumed to be isotropic in space and constant in time. There are no unique spatial or temporal variations of the CDG signal in the instrument dataspace to aid in its identification and its ultimate separation. However COMPTEL experiences a varying background environment. While these variations in the environment modulate the instrument background, they do not effect the CDG (cosmic) photons. The variations of the instrumental background and the lack of variations in the CDG radiation are used to distinguish the background from the CDG radiation. The CDG measurement is made by first subtracting all instrument background (including the atmospheric and instrumental background photons) and then attributing the residuals to the CDG radiation. To achieve this goal, a thorough understanding of the instrument background is required before effective measures can be applied for its reduction and estimation.

In this overview I will briefly discuss the low-Earth orbital environment in which COMPTEL operates. I will discuss in detail the nature of the background in the COMPTEL instrument. A large fraction of the instrument background can be understood by investigating the energy spectrum and the ToF spectrum. In addition, modulation of the count rate by the instantaneous cosmic-ray intensity and South Atlantic Anomaly (SAA) exposure also helps to identify and estimate background intensities. The various background sources exhibit a complex behavior in a multi-dimensional dataspace (e.g., energy, ToF, scatter angle, time, veto rate).

The ToF measurement is of special importance since the instrument background changes dramatically with the measured ToF. There is a strong dependence of the instrument background on the event geometry through the ToF measurement, a characteristic feature for all Compton telescopes. We will use the ToF measurement to define typical event types that constitute the COMPTEL count rates.

III. A. Nature of the Space Environment

At an orbiting altitude of ~450 km, CGRO is continuously bombarded by a large flux of energetic particles and photons from high-energy cosmic rays and secondaries produced in the spacecraft and in the Earth’s atmosphere. These high-energy particles can create one or more photons that subsequently interact in the D1 and D2 detectors and pass all the required telescope-event criteria to produce valid events. Ultimately, all the internal background events are due to photons arising from cosmic-ray (protons, electrons and heavy-nuclei) and neutron interactions with the instrument and spacecraft material.

The primary cosmic-ray particles mainly consist of protons with energies >1 GeV. Due to the enormous energy these cosmic-ray nuclei possess, a large number of secondary particles (e.g. protons, neutrons, and pions) are generated when they interact with the atmosphere or the spacecraft material. The subsequent interaction of secondary pions after their generation is the main source of cosmic-ray induced gamma rays in the upper atmosphere (Thompson 1974). Similarly, electrons produced in these interactions or from the decay of charged pions produce bremsstrahlung photons that are the main source of medium-energy atmospheric gamma rays (Daniel and Stephens 1974).

Geomagnetically trapped protons with much lower energies (1–100 MeV) are encountered when the instrument passes through the South Atlantic Anomaly (SAA). Although the trapped protons are of lower energy they are far more numerous. The daily fluence of trapped protons within the SAA for energies >100 MeV at 450 km orbit is calculated to be $\sim 1.5\times10^{6}$ cm^{2} or about 100 times the daily fluence of primary cosmic rays (Dyer et al. 1989). These protons may interact with the spacecraft to produce radioactive isotopes with long half-lives. The photons from the long-lived isotopes contribute to the measured counts outside the SAA. Since the spacecraft is turned off during SAA passages the prompt background produced during SAA passages do not contribute to the counts.

The other important component of the particle environment around COMPTEL is the neutrons (secondary particles). The neutrons in orbit are produced by the interaction of cosmic rays with the atmosphere and spacecraft material. COMPTEL can operate in a special *neutron mode* that allows for direct measurements of the neutron flux in orbit (Ryan et al. 1992). The measurements of Morris et al. (1995) indicate that the observed omnidirectional fast neutron flux (>13 MeV) can be explained by the expected albedo atmospheric neutron flux at these altitudes; which in turn implies a small relative contribution from the secondary neutrons produced in the spacecraft. Although there are large uncertainties in these measurements, preliminary simulations of high-energy protons interacting in CGRO spacecraft support these findings (Morris et al. 1995).

Neutrons with energies up to 10 MeV lose their energy by inelastic collisions of the type: $n + (N,Z) \rightarrow (N,Z)^{*} + n'$. The target nucleus is left in an excited state and may return to ground state by the emission of one or more gamma rays. Some thermalized neutrons may be captured again leaving the nucleus in an excited state. The neutrons (E_n >100 MeV) can also directly interact with the detectors to mimic gamma-ray interactions. As a result of their charge neutrality, neutrons are not vetoed by the shields and constitute a significant background source.

The Earth is an intense source of gamma rays. These atmospheric gamma rays can also contribute to the overall count rate as the Earth moves across the instrument's field-of-view.

The atmospheric gamma rays constitute a background source while making celestial gamma-ray measurements.

III.B. Nature of the COMPTEL Background

The varying background environment is one of the advantages enjoyed by COMPTEL. The dynamic nature of the background is exploited to the fullest in making the CDG measurement. Figure III.1 shows the modulation in Gamma-1 rates, veto2-scalers, cutoff-rigidity and geocentric-elevation angle (GCEL, the angle between the pointing direction and the center of the Earth) for a typical day (TJD 9725) in orbit. The Gamma-1 rate is the measured signal in-flight prior to any data selections and shows a large modulation due to the background sources.

The CGRO orbital period is 96 minutes resulting in about 15 orbits a day. This is seen in the modulation of the GCEL angle as the Earth moves across the COMPTEL field-of-view (figure III.1). The Earth is a strong source of gamma-rays over a wide energy range. The dependence of the event rate on GCEL arises from the passage of the Earth across the COMPTEL aperture (the Earth subtends a wide angle of ~70˚). By applying FoV selections and judicious choice of observation times, the contributions of the atmospheric gamma rays can be completely eliminated during the CDG analysis (see section IV.B).

The instrument passes through the SAA from 6 to 8 times a day. The increase and subsequent decrease in the instrumental radioactivity when passing through the SAA is clearly visible in the Gamma-1 rate near the beginning of the day (figure III.1). The activated isotopes can have a broad range of decay times but are present at energies only below 4.2 MeV. The variations for the SAA-induced activation background source depends on the history of activation, in terms of dosage since launch and on the half-life of the individual isotope. Since the background from these sources is not related to the instantaneous particle environment, but dependent on the total activation history, the background source is referred to as the *long-lived* background component. Any natural radioactivity in the spacecraft mass will also be included in this long-lived component. An example of natural radioactivity is the ^{40}K ($\tau_{1/2}$ ~ 10^6 years) contained in the glass of the PMTs in D1 and veto assembly.

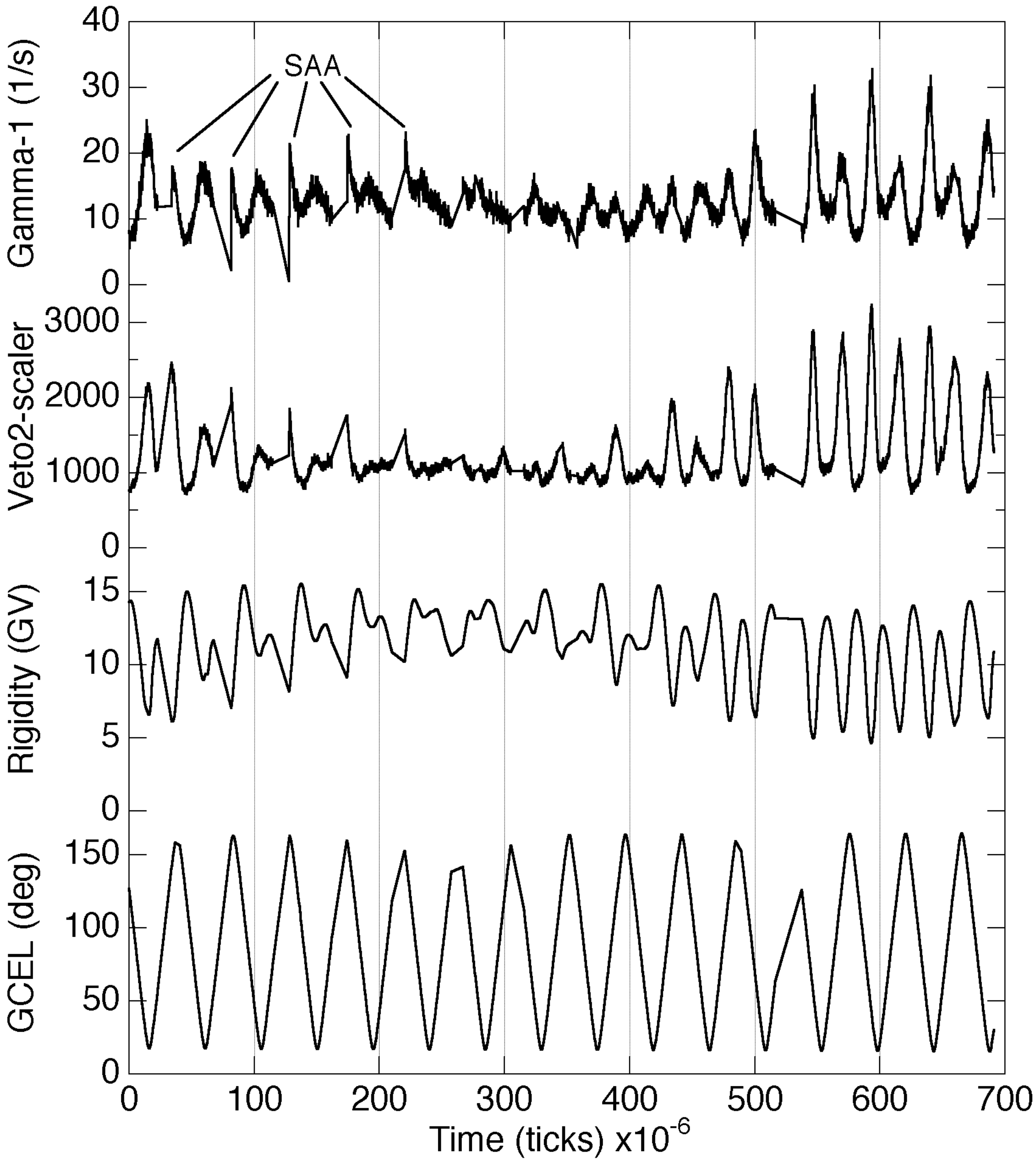

Figure III.1 The modulation in Gamma-1 event rates, veto2-scaler, rigidity and GCEL observed in a typical day (TJD 9725).

The variations of the cosmic-ray intensity in orbit are expected to correlate with the vertical cutoff-rigidity as CGRO traverses different points with respect to the Earth's magnetic field. The low-energy cutoff for the cosmic rays are usually expressed in terms of the vertical cutoff-rigidity R defined as pc/Ze. In general, particles cannot reach locations where the local cutoff-rigidity is greater than the rigidity of the particle. For a typical CGRO orbit, the cutoff-rigidity varies from 4 to 16 GV corresponding to proton cutoff-energies around 4 to 16 GeV, respectively. The modulation of the measured Gamma-1 rate with the cutoff rigidity is evident in figure III.1. Since a lower cutoff-rigidity ensures a lower cutoff-energy, more cosmic-ray particles are allowed to reach the spacecraft location and produce a higher background rate. The inverse correlation between the rigidity and the event rate is shown in figure III.2. This modulation of count rate with rigidity has been observed in other detectors (e.g., SMM (Forrest 1989), Kosmos-461 (Mazets et al. 1975)) and the measured rates have often been described by an exponential function in rigidity.

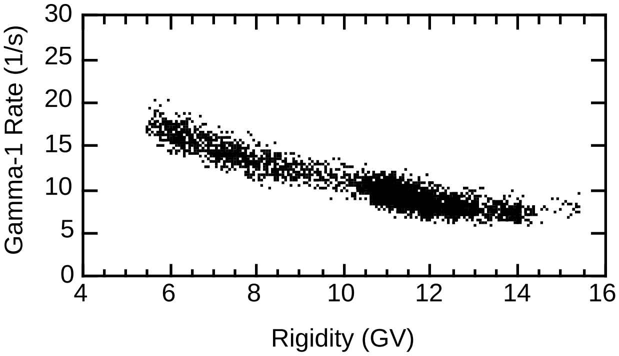

Figure III.2 The distribution of Gamma-1 event rates as a function of the vertical cutoff-rigidity for a typical viewing period (VP 408). The data is accumulated for sky-pointing when the instrument is well outside the SAA (time>30 min).

The veto rates are a direct measure of the instantaneous cosmic-ray flux incident on COMPTEL and, as such, show a strong anti-correlation with the cutoff rigidity (see figure III.1). High energy gamma rays could trigger the veto domes but their efficiency is low since the veto domes are designed to be transparent to medium-energy gamma rays (see section II.B). Since the veto signals are dominated by charged cosmic rays, a zero veto rate corresponds to zero cosmic-ray intensity. The measured Gamma-1 count rate modulates linearly with the veto rates as shown in figure III.3. Any background that modulates with the local instantaneous cosmic-ray flux is called *prompt* background. The presence of the veto shields requires proton and electron interaction locations to lie outside the veto domes if they are to produce prompt events. The prompt background internal to COMPTEL is predominantly due to the neutron flux.

The prompt background is present at all energies from 0.8 to 30 MeV. The spectrum is predominantly a continuum between 1 and 10 MeV due to nuclear interactions. The liquid scintillator that constitute the D1 detector serves as a efficient moderator of neutrons. The hydrogen in the scintillator can capture a thermal neutron (n + H → D + γ) giving rise to 2.223 MeV photon. Since the time scale for moderation and absorption is about 100 μs, it is prompt emission with respect to COMPTEL. The 2.223 MeV photons are produced within the D1 detector and can produce telescope events with high efficiency. The 2.223 MeV is a prompt and intense instrumental line. It has been used to probe the nature of the prompt background (see section V.E).

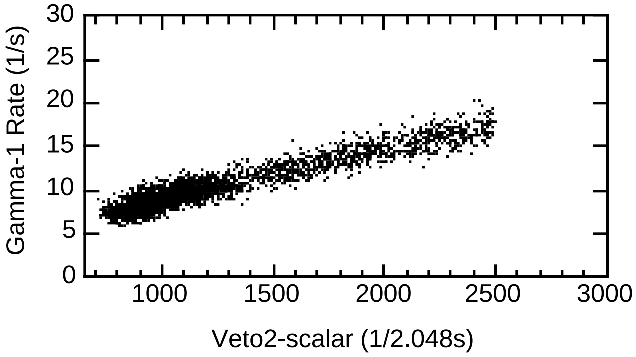

Figure III.3 The distribution of Gamma-1 event rates as a function of the veto2-scaler for a typical viewing period (VP 408). The data is accumulated for sky-pointing when the instrument is well outside the SAA (time>30 min).

Besides the correlation of the instrument background with orbital parameters. The measured event parameters for each event can be used to improve the signal in the measurements. Of the measured event parameters the time-of-flight (ToF) measurement, the total energy (ETOT) and the scatter angle (ϕ) are most important.

The Gamma-1 ToF spectrum can be well described by a gaussian peak at channel 120 superimposed over a smooth continuum. A typical ToF spectrum is shown in figure III.4. The ToF-peak includes among other things the external photon counts (the signal). The continuum events are from accidental coincidences and other local photon events. Note that of all the Gamma-1 counts, only the peak region between channels 110 and 130 contains counts that come from external cosmic sources.

In the CDG analysis, the ToF spectra are fit to determine the counts in the ToF peak. This eliminates on a statistical basis a large fraction of the background due the ToF-continuum. However, we must now determine the background within the ToF peak before arriving at the desired CDG event rate.

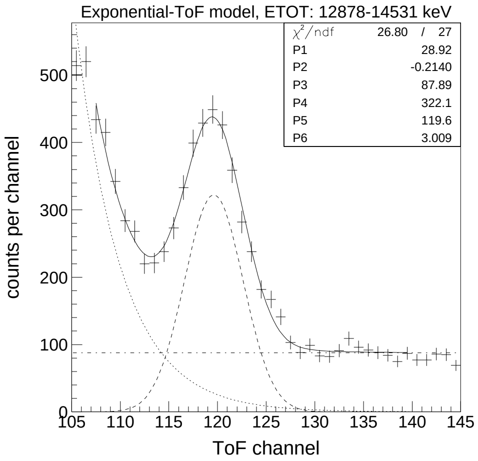

Figure III.4 A typical time-of-flight spectrum for sky observations.

By fitting the ToF spectrum for various energy intervals one can construct the count spectrum for the ToF-peak component. The energy spectrum consists of prompt and long-lived background in additional to the CDG signal. The ToF-peak energy spectrum below 4.8 MeV is plotted in figures III.5. There are three prominent structures on top of a smooth continuum. At 2.223 MeV we see the deuterium line from thermal neutron capture by the hydrogen in D1. There is a broad emission structure from 2.7 to 4.2 MeV, largely due to the decay of ^{24}Na where two independent photons (1.368 and 2.754 MeV) give the total energy. The complex feature near 1.5 MeV contains contributions from ^{40}K (1.46 MeV), from ^{22}Na (0.511 and 1.275 MeV) and other unidentified emission lines. The important point is that by examining the E2 (or ETOT) spectrum we can identify line emission from radioactive isotopes. The energy spectrum is fit to estimate their intensities. The contributions from all radioactive isotopes can then be subtracted from the data.

The raw COMPTEL event rate shows a complex behavior with orbital parameters and with the measured event parameters. The raw Gamma-1 rate varies on many time scales due to the prompt cosmic-ray intensity, the modulation of atmospheric photons and the effects of long-lived radioactive decay. The Gamma-1 rate typically varies by a factor of 6. The veto rate and time after SAA are the strongest modulators of the background. There are indications for long-term variability of the instrumental background at energies below 4.2 MeV, related to the reboost of CGRO (see section V.B). The azimuthal orientation of the instrument and the phase in the solar-cycle may also introduce additional modulations in the measured rates. A neural-network approach for modeling the COMPTEL background has shown that the Gamma-1 rates can be reasonably well described by the following five independent parameters (Varendorff et al. 1996),

1) the position of the Earth in the FoV (azimuth and elevation).

2) the geographical position of the satellite (longitude and latitude).

3) the longitude of the ascending node of the orbit.

4) the altitude of the spacecraft.

5) the geocentric elevation angle.

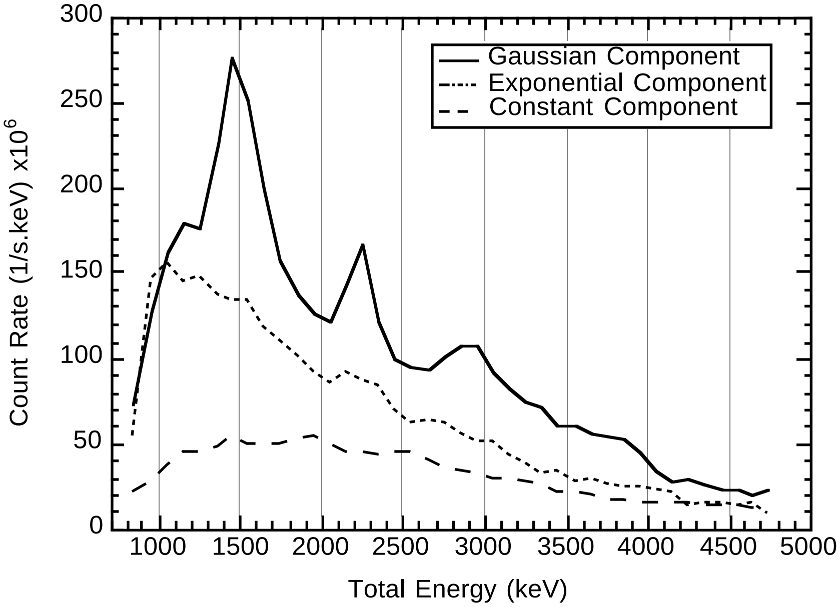

Figure III.5 The total energy count spectrum for the three different ToF components in linear scale from 800 to 4800 keV.

III.C. Protons, Neutrons and Electrons

Neutrons constitute a significant background source because of their ability to mimic gamma-ray events. Both prompt and delayed gamma-ray emission following neutron interactions anywhere in CGRO can trigger valid events. Because of the presence of the veto subsystem, prompt emission from protons interactions anywhere within the instrument is not an important source of background.

In general, any delayed emission ($\tau_{1/2}$ >130–170 ns) from cosmic-ray interactions within or outside COMPTEL could interact to produce background events. The detection efficiency is greatest when the interactions occur within COMPTEL. When the time scales for delayed emission are more than a few minutes they contribute to the long-lived component. The trapped protons in the SAA will also interact with the spacecraft and the instrument to produce radioactive isotopes with long half-lives. Therefore, protons interactions could contribute to the long-lived background component.

At photon energies above ~10 MeV, electrons may also be important since, on average, they tend to lose most of their energy by emission of only a few energetic bremsstrahlung photons. These interactions must also occur outside the detector or the events will be vetoed. The electron-induced component is prompt in nature and does not induce radioactivity.

III. D. Background Event Geometry

Valid events can be created in many ways by the local particle and photon environment surrounding COMPTEL. For example, showers or multiple gamma rays originating within the instrument (especially near D1) can produce valid events even after all the data selections. The measured ToF value will depend on the point of origin of the photons relative to the locations of the modules. Thus, ToF serves as a useful parameter by which we can examine and identify background sources.

I will now define certain event mechanisms or geometries by which single or multiple photons surrounding COMPTEL can produce valid events. Assuming that the other event parameters are within valid ranges, the main channels of background event production can be separated into four basic geometries: Types A, B, C and D, defined below and illustrated in figure III.6.

Type A: Events caused by single photons that scatter from D1 into D2, i.e., scatter-photon events. Any photon (local or external) may produce this type of event if it first scatters in D1 and then interacts in D2. This is how cosmic radiation is detected and measured by the COMPTEL instrument. Ideally, the gamma ray along with its secondaries will be stopped in the two detectors with an accurate determination of the event location. The events will have the nominal ToF value of ~5 ns or channel 120. These scattered-photon events are present in a gaussian-like ToF peak at the expected position (see figure III.4).

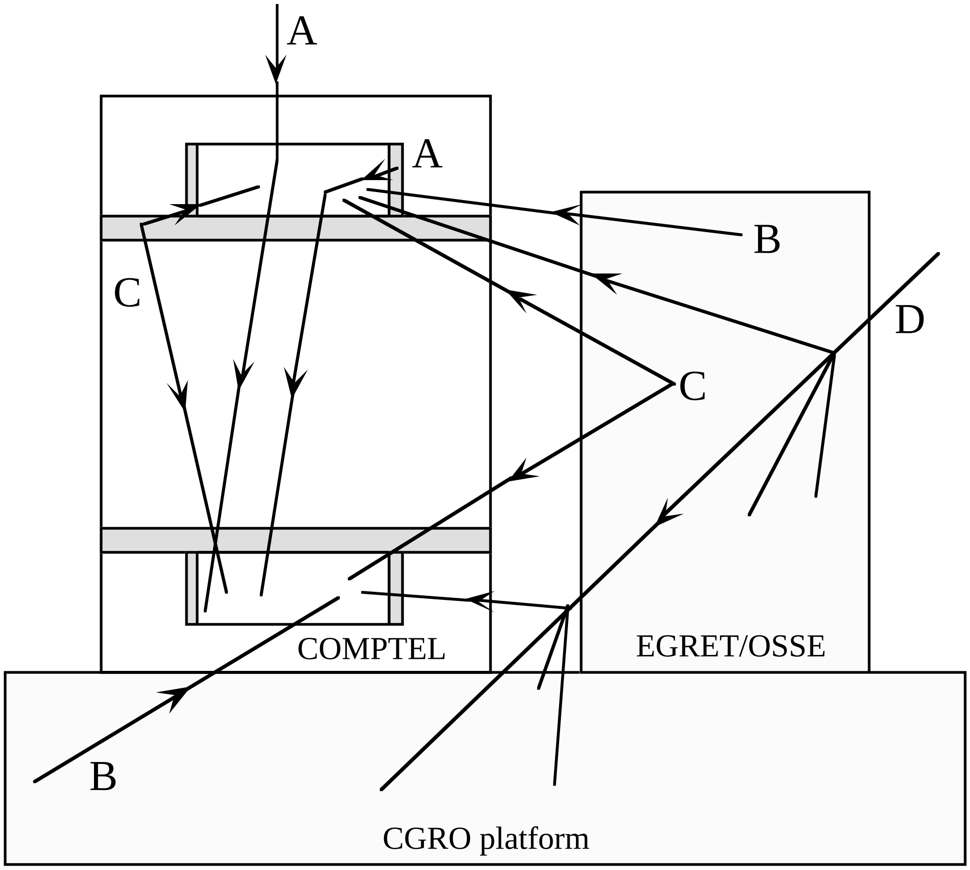

Figure III.6 A COMPTEL cartoon to illustrate the various background event types. For the sake of simplicity only one D1 and one D2 module is shown. The mass around and below are also shown by the dotted region, representative of the spacecraft platform and the other CGRO instruments.

Most photons from below D1 will require large-angle scatters in D1 to be able to travel towards D2. During a large angle scatter the photon loses most of its energy in D1 resulting in a low energy photon in D2. The standard-CDG event selection on scatter angle (< 38˚) and D2 energy threshold (> 730 keV) eliminates most of these events. An example is the rejection of 1.46 MeV photons from the natural decay of ^{40}K in the EGRET spark-chamber.

However, local photons originating in and around the D1 detector (e.g., detector housing, D1 reservoirs) or above the D1 assembly (e.g., veto covers) can have low scatter angles, i.e., the same scattering geometry of cosmic photons. These photons constitute the dominant single-photon background events that contaminate the signal at channel 120. The instrumental lines at 1.46 MeV (from the ^{40}K in the D1 PMTs) and 2.223 MeV (from thermal neutron-capture by the H in D1) are good examples of such background events (see section V.C).

In principle, high-energy neutrons can scatter in the D1 scintillator and continue on their paths to interact in D2, or a secondary photon produced in the neutron interaction in D1 trigger D2, to mimic scattered-photon events. The PSD is used to suppress such events (see section II.B).

Type B: Events caused by two independent photons that are temporally and spatially uncorrelated, i.e., accidental events. In orbit, COMPTEL is exposed to a large flux of photons, mainly of local and atmospheric origin. Occasionally two unrelated (temporally and spatially) photons will independently interact with each of the two detectors (D1 and D2) within the 40 ns ToF window to produce an acceptable telescope event. Since these events are not correlated in time, they are distributed uniformly in ToF space (see figure III.4). This uniform ToF signature is used to identify and isolate the accidental-event background component.

Type C: Events caused by two or more photons that have the same origin and are emitted nearly simultaneously, i.e., multiple-photon events. When two photons are emitted within <<1 ns of one another, a typical time scale for electromagnetic nuclear decays, and one photon triggers a D1 and the other photon triggers a D2 module, a valid event is registered. The measured ToF value depends on the site of the decay relative to the modules. If the origin is to one side of the instrument between D1 and D2 then the signals in D1 and D2 are near simultaneous. For origins around and below D2 the ToF value is negative, while for positions around D1 the ToF value is positive. Photons originate from all the material around the detectors resulting in a continuum in ToF space (origins above D1 cannot result in ToF values greater than 5 ns). Such events fill the regions between the forward and backward peaks (van Dijk 1996) and produce a ToF component that vanishes above channel 120 (see figure III.4).

The concentration in mass in the D1 assembly produces an excess of these events around channel 120. For two-photon events originating in or near D1, the travel time for one photon to a D1 module is short but significant while the other photon has a travel time to D2 of ~5 ns. The resulting type C event from the D1 assembly has a ToF value of <5 ns. With the ToF resolution it is not easy to separate this component from that at channel 120. These events are often included in the gaussian component of the ToF spectrum.

The physical process leading to such events is cascading nuclear de-excitations where nuclei are excited to high quantum states (by proton or neutron collisions) and then decay by multiple-photon emission on short time-scales ($\tau_{1/2}$ < 1 ns). Events are also possible when nuclei de-excite by single photon emission via beta-decay and the bremsstrahlung or annihilation photon from the $\beta^{\pm}$ particle fills the role of the second gamma ray.

Events may also be produced by fast neutrons that excite a nucleus around D1 (whose decay photon subsequently interacts with a D1 detector) and continues on its path to interact (directly or indirectly) in the D2 detector. The neutrons must necessarily be fast (E_n >100 MeV) to satisfy the 40 ns ToF coincidence window. These neutron events can give a broad range of ToF values with an absolute minimum ToF value of 5 ns.

Type D: Events from multiple photons that are temporally correlated but spatially unrelated i.e., the shower events. High-energy cosmic rays produce electromagnetic showers in the spacecraft. Two photons from different parts of the shower can interact with the two detectors to produce a valid event. Since the shower particles are usually relativistic, photons arriving from different parts of the shower have the proper time delays. These events produce a broad range of possible ToF values. However, for showering particles to register an event, no charged particle (protons, electrons or pions) can penetrate the veto system.

The above overview of the background events in terms of their geometry and mechanism presents a simplified picture of the instrument background. For example, there may be direct ionizational losses from the beta-particles originating in the D1 housing or other more complex photon production mechanisms. The geometrical dependence of the background in COMPTEL is a unique feature common for all Compton telescopes.