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Neutron Induced Background in the COMPTEL Detector on the Gamma Ray Observatory

D.J. Morris[3], H. Aarts[2], K. Bennett[4], M. Busetta[4], R. Byrd[5], W. Collmar[1], A. Connors[3], R. Diehl[1], G. Eymann[4], C. Foster[5], J.W. den Herder[2], W. Hermsen[2], M. Kippen[3], L. Kuiper[2], J. Lockwood[3], J. Macri[3], M. McConnell[3], R. Much[1], J. Ryan[3], V. Schönfelder[1], G. Simpson[3], M. Snelling[4], G. Stacy[3], H. Steinle[1], A. Strong[1], B. Swanenburg[2], B.G. Taylor[4], T. Taddeucci[5], M. Varendorff[1], C. de Vries, and C. Winkler[4]

[1]*Max-Planck Institut für extraterrestrische Physik, Garching, FRG*
[2]*Laboratory for Space Research Leiden, Leiden, The Netherlands*
[3]*Space Science Center, University of New Hampshire, Durham NH 03824, USA*
[4]*Space Science Department, ESTEC, Noordwijk, The Netherlands*
[5]*Indiana University Cyclotron Facility, Bloomington IN 47504, USA*

Abstract

Interactions of neutrons in a prototype of the Comptel gamma-ray detector for the Gamma Ray Observatory were studied at the Indiana University Cyclotron Facility (IUCF) both to determine Comptel's sensitivity as a neutron telescope and to estimate the gamma-ray background resulting from neutron interactions. The IUCF provided a pulsed neutron beam at five different energies between 18 and 200 MeV. These measurements showed that the gamma-ray background from neutron interactions is greater than previously expected. It was thought that most such events would be due to interactions in the upper (D1) detector modules of Comptel and could be distinguished by pulse-shape discrimination. Rather, the bulk of the gamma-ray background appears to be due to interactions in passive material, primarily aluminum, surrounding the D1 modules. In a considerable fraction of these interactions two or more gamma-rays are produced simultaneously, with one interacting in a D1 module and another interacting in a module of the lower (D2) detector; if the neutron interacts near the D1 module, the D1-D2 time-of-flight cannot distinguish such an event from a true gamma-ray event. In order to assess the significance of this background the flux of neutrons in orbit has been estimated based on observed events with neutron pulse-shape signature in D1. The strength of the neutron-induced background is estimated. This is compared with the rate expected from the isotropic cosmic gamma-ray flux.

1. INTRODUCTION

One of the greatest difficulties in the medium energy γ-ray range (1-30 MeV) studied by Comptel [1] on the Arthur Holly Compton Gamma Ray Observatory is the large instrumental backgrounds from which astronomical γ-ray emission must be distinguished. While Comptel employs several effective strategies to reduce background [2], it is still a serious problem, particularly for observations of diffuse astronomical radiation. This problem is greatest for the apparently isotropic cosmic background radiation.

An important component of the instrumental background – prompt events produced by neutron interactions within the instrument – is the subject of this paper. This background was studied on the ground by exposing an advanced prototype of the Comptel experiment (referred to as Science Model III or SM3) to a pulsed neutron beam. These measurements showed that the prompt neutron-induced background was much larger than expected. Most of these background events are attributed to interactions of neutrons in passive material near the upper (D1) detector modules.

In order to judge the impact of this background on the sensitivity of Comptel, the neutron flux incident on the D1 detector in the Gamma Ray Observatory orbit must be known. This flux has been estimated from measurements made with the Comptel instrument in a special mode, using one of the D1 modules as an isotropic neutron detector. The in-flight neutron flux is smaller than that observed by balloon experiments at similar latitudes [3], but appears to have a harder spectrum. Combining the estimated in-flight flux with the SM3 results produces an estimate of the rate of prompt neutron-induced γ-like events. This rate is a large fraction of the rate expected for cosmic-diffuse events.

2. SCIENCE MODEL III NEUTRON CALIBRATION

The SM3 instrument consisted of two D1 modules and three of the lower modules (D2) identical to those in the flight instrument [1]. The D1 and D2 modules were mounted separately on two circular aluminum plates reinforced with aluminum beams, similar to those in the flight model. These plates in turn were mounted on a framework of aluminum beams together with one ^{60}Co calibration unit and an anticoincidence detector, consisting of a square plate of plastic scintillator viewed by eight photomultiplier tubes, placed behind one of the D1 modules. Electronics boxes were mounted on top of the aluminum framework. The lines of sight between D1 and D2 modules were unobstructed, except by the anticoincidence detector. The six D1-D2 pairs (referred to as minitelescopes) provided a variety of γ-ray scattering angles, ranging from 1.8° to 30.2° for normal incidence.

The SM3 instrument was exposed to a tagged neutron beam at the Indiana University Cyclotron Facility. Pulses of protons were directed at a ^{7}Li target to produce neutrons via the reaction $^{7}Li(p,n)^{7}Be$. Energy loss by the protons in the target reduced the mean energy of the neutrons below that of the incident proton beam and introduced an energy spread which was greater at low energies. The neutron beam was directed at the SM3 instrument located in a hut 46 m from the ^{7}Li target, behind a Styrofoam filled window; at that distance the beam width was about 1.5 m. At normal incidence, data were obtained with five mean neutron energies: 18.5, 35.7, 77.0, 132.1, and 198.1 MeV. At the four higher energies data were obtained for incidence angles of 45° and 135°; at 35.7 and 132.1 MeV data were also obtained at 90° incidence.

Quantities measured for each event in the Comptel detector include energy deposits in the D1 and D2 detectors, a D1-D2 time of flight (TOF), and a D1 pulse shape (PSD). A neutron time-of-flight from the ^{7}Li target was also recorded for each SM3 event, allowing selection of events coincident with the neutron pulse. Several additional requirements were set for prompt γ-like events in SM3. Only events having a PSD value consistent with a scattered photon were selected. Threshold energies of 200 keV and 500 keV were set for the D1 and D2 detectors, respectively; for D1 energies below 200 keV the PSD is ambiguous. A 5 ns wide TOF window was chosen for each minitelescope. Events coincident with an anticoincidence signal were not accepted, which is consistent with the requirements for γ-like events in Comptel. Finally, the Compton scatter angle inferred from the D1 and D2 energy deposits had to be less than 30°.

Based on measurements with the simpler Double Compton Telescope (DCT) of Schönfelder and Daugherty [4], it was assumed that most neutron-induced γ-like events were the result of $^{12}C(n,\gamma)$ interactions in the NE213 liquid scintillator in the D1 modules (Fig. 1a); most other interactions in the scintillator will produce a proton or alpha particle, and can be distinguished by the PSD. Taking into account differences between the DCT and SM3 detectors, the probability for a neutron entering D1 to produce a γ-like event was expected to be a factor of 15 smaller in a single SM3 minitelescope than in DCT. Surprisingly, analysis of data from one SM3 minitelescope with event selections similar to those used for DCT showed the probabilities in the two cases to be nearly the same!

This discrepancy between the response of the DCT and Comptel detectors is resolved if most of the γ-like events in SM3 actually resulted from neutron interactions in passive material surrounding the D1 detectors, most of which is aluminum. The neutron interaction leaves an excited nucleus which promptly decays via a gamma cascade, emitting two or more photons (Fig.

1b). One of these photons scatters in a D1 module, providing a photon pulse shape; another interacts in D2, providing a γ-TOF. For neutron energies above 100 MeV the scattered neutron may also reach D2 quickly enough to provide a γ-TOF (Fig. 1c). In the DCT detector there were few such events because the mass of the D1 housing was much smaller than in SM3 (1.2 kg vs. 3.4 kg), and the DCT experiment used a collimated neutron beam with dimensions slightly smaller than those of the DCT D1 detector.

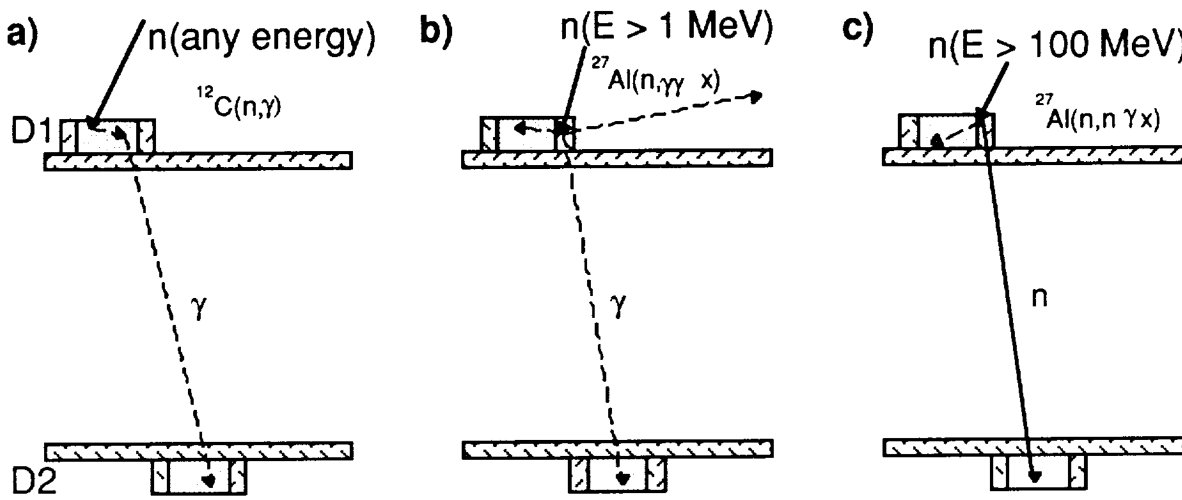

Figure 1: a)*The* $^{12}C(n,\gamma)$ *reaction formerly thought to be most important in producing prompt neutron-induced background;* (b) *and* (c) *illustrate the interactions occurring in passive material near the D1 modules which the SM3 measurements suggest are much more important.*

Published non-elastic $^{26}Al(n)$ cross-sections, which are available for neutron energies up to 100 MeV or more [5-9], can be used to demonstrate the plausibility of this explanation of the SM3 results. Unfortunately, photon multiplicity distributions for such interactions, which are needed to prove or disprove this hypothesis, are not available. An experiment similar to SM3, but varying the passive mass near D1, could provide more convincing evidence for this hypothesis. To show that the SM3 results are consistent with the published cross sections, the cross-section for a neutron to produce a γ-like event in one minitelescope, referred to here as σ_{SM3}, has been determined from the measurements. This quantity can be related to the non-elastic $^{26}Al(n)$ cross-section, σ_{non}, and the cascade photon multiplicity, m:

$$\sigma_{SM3} = [0.33\langle m\rangle + \langle m(m-1)\rangle]\ \sigma_{non}$$

Pointed brackets in this expression indicate the mean of the enclosed quantities. The first term within the square brackets accounts for events in which a single photon scatters from D1 to D2, while the second accounts for two-photon events of the type illustrated in Fig. 1b. Figure 2 compares σ_{SM3}, as measured in a single minitelescope with normally incident neutrons, to published cross-sections. At neutron energies from 18 to 77 MeV the ratio $\sigma_{non}/\sigma_{SM3}$ is about 4, consistent with a mean photon multiplicity $<m>$ of 2.4 or less; at energies 15 to 50 MeV $<m>$ is in the range 1.7 to 2 [9]. Above 100 MeV $\sigma_{non}/\sigma_{SM3}$ increases, probably due to high-energy neutrons scattering to D2, as in Fig. 1c; such interactions are not included in the expression for σ_{SM3} above.

The plausibility of this hypothesis can also be demonstrated by the presence of features in the D2 energy spectrum, where a strong line should produce a visible photopeak. The sum of D2 spectra in all three modules for the 35.7 MeV-135° runs shows such a feature at 1.5-2.0 MeV, consistent with a line at 1.81 MeV produced from the reaction $^{27}Al(n,d\gamma)^{26}Mg$. The statistics of the 18.5 MeV data were not sufficient to pick out such a feature; at higher neutron energies such features are weaker relative to the continuum [10].

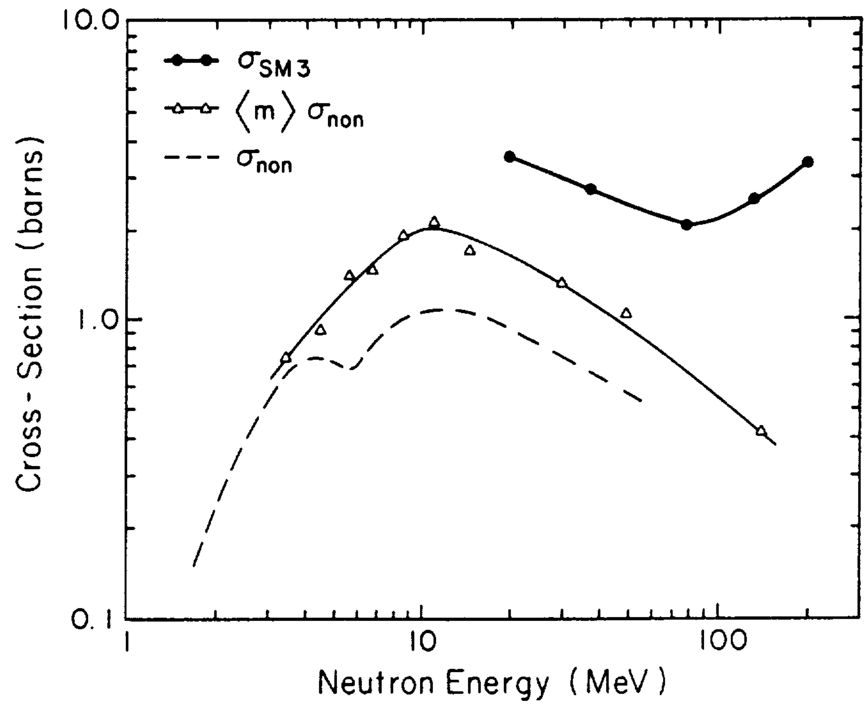

Figure 2: *Comparison of the quantity σ_{SM3}, estimated from events in a single SM3 minitelescope, with published non-elastic $^{27}Al(n)$ cross-sections (σ_{non}, refs. 5-7) and with the non-elastic cross section multiplied by the mean photon multiplicity ($<m>\sigma_{non}$, refs. 8 and 9).*

The probability that an incident neutron produces a γ-like event, as a function of the measured event energy, incident neutron energy, and incidence angle, was evaluated separately for each SM3 minitelescope. The probabilities varied considerably between minitelescopes but most of this variation could be attributed to the differences in D1-D2 distance for each minitelescope; the remaining discrepancies were on the order of 20% averaged over neutron energy and angle. Variations with incidence angle were relatively small. The results for individual minitelescopes were multiplied by a factor to correct the D1-D2 distance to that of a 'mean' Comptel minitelescope and then averaged. The cross section for a neutron to produce a γ-like event in the mean minitelescope, integrated over event energy, is in the range 0.008-0.014 cm^2. The cross section is greatest at 18.5 MeV incident energy and appears to have a minimum near 100 MeV, as in Fig. 2. As a function of the event energy measured in SM3 (as opposed to the incident neutron energy), the cross section falls slowly over the range 1 to 5 MeV, very steeply beyond that; few events with energies above 10 MeV were seen, and then only with incident neutrons above 100 MeV.

The lack of SM3 data for neutron energies above 200 MeV introduces large uncertainties in the γ-like background estimate, especially at higher event energies. While the SM3 cross section increases above neutron energy 100 MeV, this increase probably stops at some point where most scattered neutrons have enough energy to reach D2 and produce a γ-TOF. At some energy self-veto effects with the full anticoincidence system may also become important in Comptel, hence reducing the cross section for γ-like events.

3. ORBITAL NEUTRON FLUX

The neutron flux incident on the D1 detectors in flight has been estimated from a special 26 minute measurement made during earth occultation on 8 July 1991. All D2 modules and all but one D1 module were turned off. The one remaining D1 module was operated with a very high threshold, 8 MeV. In this 'singles' mode, a coincidence with a D2 module is not required, although events can still be vetoed by signals from the anticoincidence domes. The event rate in this configuration was 30-100% of the telemetry capacity; lowering the threshold or using additional modules would lead to deadtime uncertainties without appreciably increasing the event rate.

The neutron sensitivity of a D1 module in the singles mode was calculated as a function of the neutron energy and D1 threshold by Byrd [11]. The orbital observations cannot be easily deconvolved to produce a definitive value for the neutron flux or a shape for the energy spectrum. Instead, some possible energy spectra have been folded with the sensitivity to predict a neutron detection rate; these predicted rates are compared with those observed to determine whether the flux is greater or less than that expected, and/or whether the spectrum is harder or softer.

The D1-singles events are divided into two groups based on energy: above and below 20 MeV, the highest energy at which the D1 energy and PSD were calibrated. For events outside the calibrated range (above 20 MeV) the energy can only be considered a lower limit, but neutron events can still be distinguished by their PSD signatures. It is also useful to divide the events into two periods based on the cosmic-ray vertical cutoff rigidities due to the geomagnetic field. During the first 16 minutes of the measurement the cutoff rigidity was high and nearly constant, in the range 10.5-12.5 GV. During the remaining 10 minutes the cutoff rigidity dropped rapidly from 10.5 GV to ~5 GV. About 58% of the neutron events occurred during the shorter low cutoff rigidity period.

TABLE I
D1 NEUTRON SINGLES EVENT RATES

Event Energies (MeV)	Event Rates (Hz)			
	High Vertical Cutoff Rigidity (10.5-12.5 GV)	Low Vertical Cutoff Rigidity (~5-10.5 GV)	Balloon Flight(1)	$E^{-1.3}$ Energy Spectrum
< 8.	0.07	0.18	—	—
8. - 20.	0.78	1.80	2.70	2.08
>20.	0.78	1.58	1.30	1.86
All	1.63	3.56	4.00	3.94

(1)Ait-Ouamer [10]

Table 1 lists the rates of neutron-singles events in both high and low cutoff rigidity periods in three D1 energy ranges. About 10% of the events below 20 MeV also fall below the nominal 8 MeV threshold after the events are corrected for photomultiplier gain variations. Also shown in this table are the rates expected for a neutron flux such as that seen by Ait-Ouamer [3] at balloon altitudes at a vertical cutoff rigidity of 8.5 GV, with a neutron energy spectrum having a power law index of −1.61. The last column shows the rates for a power-law spectrum of index -1.3 and with the total flux above 10 MeV normalized to that seen by Ait-Ouamer.

While the Ait-Ouamer neutron energy spectrum is much softer than that inferred from the D1 singles data, the $E^{-1.3}$ spectrum is consistent with the D1 singles data in the low cutoff rigidity range. Simulations with a preliminary mass model indicate that the neutrons produced in the spacecraft have a harder spectrum than those from the atmosphere [12], though perhaps not as hard as $E^{-1.3}$. The total count rate at low rigidity is about 10% lower than that expected from the Ait-Ouamer measurements. This difference is well within the uncertainties in the calculated D1 singles neutron sensitivity.

4. ESTIMATED STRENGTH OF THE NEUTRON-INDUCED BACKGROUND

By folding the cross sections derived for SM3 (section 2) with an estimated neutron flux and energy spectrum into D1 (section 3), the strength of the neutron-induced background can be estimated. However, the cross sections for the mean SM3 minitelescope must first be multiplied by two factors to account for differences between SM3 and Comptel: a factor of 98 to include all the Comptel minitelescopes, and a factor of 1.5 to account for the greater amount of passive material near the D1 modules in Comptel. The latter factor is very uncertain; a better estimate may be obtained by comparing the 18.5 MeV SM3 data with calibration data for the Comptel flight model obtained using a 17 MeV neutron beam.

TABLE II
EXPECTED RATES OF NEUTRON-INDUCED GAMMA-LIKE EVENTS (Hz)

	Event Energy (MeV)				
Neutron Spectrum	1.0-3.0	3.0-5.0	5.0-10.0	10.0-30.0	0.0-50.0
10-250 MeV Neutrons					
Ait-Ouamer	0.08	0.05	0.030	0.0007	0.1578
$E^{-1.3}$	0.05	0.03	0.019	0.0007	0.0986
>10 MeV Neutrons					
Ait-Ouamer	0.09	0.06	0.035	0.0022	0.1828
$E^{-1.3}$	0.08	0.05	0.029	0.0045	0.1596
Isotropic Cosmic Flux	0.10	0.09	0.023	0.0060	

Expected rates of neutron-induced γ-like events for two different incident neutron spectra are presented in Table II. The two neutron spectra are Ait-Ouamer's spectrum, and the $E^{-1.3}$ spectrum with a total fluence above 10 MeV 10% lower than Ait-Ouamer's. Two rate estimates are given for each neutron spectrum: one for incident neutrons in the energy range 10-250 MeV only, and one for all incident neutrons above 10 MeV. For this second estimate the SM3 probabilities for 198.1 MeV neutrons are used for the incident neutrons above 250 MeV. These results imply that the high-energy neutrons are very important for event energies above 10 MeV; with the harder neutron spectrum they may also be important for the lower event energies. Thus there is a large uncertainty in the neutron-induced background rate, especially in the upper part of the Comptel energy range, depending on how the SM3 results are extrapolated to higher neutron energies. These background estimates are compared with the rate of events expected from an isotropic cosmic γ-ray flux, based on previous spacecraft observations [13] which were folded with the Comptel sensitivity; this sensitivity was determined from simulations with a mass model of Comptel, using the same event selections as in the SM3 analysis.

A comparison of the neutron-induced γ-like background rates with the expected rate of cosmic diffuse events, shows that this instrumental background may be a large fraction of the event rate from the isotropic cosmic γ-ray flux at all event energies. At high cutoff rigidities, the background rates will be reduced by about a factor of two, but that level is still quite significant. It should be noted that both the neutron-induced background rates and the cosmic-diffuse rates depend on the event selections imposed; in particular, the high D1 threshold used in the SM3 analysis reduces the cosmic diffuse rate in the 1-3 MeV range by about a factor of three relative to the standard Comptel selections. A carefully chosen set of selections may increase the rate of events from the isotropic cosmic γ-ray flux relative to the instrumental background.

5. CONCLUSIONS

It is clear that the instrumental backgrounds in the Comptel γ-ray telescope, and indeed in all instruments operating in this γ-ray energy range, must be carefully accounted for in order to determine a reliable flux for the cosmic-diffuse radiation. An analysis such as that presented here is a necessary part of that process. The neutron-induced γ-like background is an important part of the instrumental background, perhaps the dominant part at certain event energies. This analysis may be improved in a number of ways: a) by further in-flight neutron singles measurements to better estimate the neutron flux into D1 as a function of rigidity, and to look for dependence on spacecraft orientation; b) by more accurate calculation of the D1 neutron singles sensitivity; c) by optimizing the event selection parameters and reanalysis of the SM3 data with the optimal selections; and (d) by analysis of the 17 MeV neutron calibration data to allow more reliable application of SM3 results to Comptel.

Other approaches will certainly be important in a full background analysis. In particular correlations must be sought between the gamma event rate, as a function of energy and direction within the field-of-view, and such quantities as magnetic rigidity and spacecraft orientation. However extrapolation from those measurements to infinite rigidity will still depend on laboratory measurements such as SM3, and their interpretation.

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