COMPTEL AS A SOLAR GAMMA RAY AND NEUTRON DETECTOR

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ABSTRACT

The imaging Compton telescope COMPTEL on the Gamma Ray Observatory has unusual spectroscopic capabilities for measuring solar γ-ray and neutron emissions. Flares can be observed above the 800 keV γ-ray threshold of the telescope. The telescope energy range extends to 30 MeV with high time resolution burst spectra available from 0.1 to 10 MeV. Strong Compton tail suppression facilitates improved spectral analysis of solar flare γ-ray emissions. In addition, the high signal-to-noise ratio for neutron detection and measurement provides new neutron spectroscopic capabilities. For example, a flare similar to that of 1982 June 3 will yield spectroscopic data on > 1500 individual neutrons, enough to construct an unambiguous spectrum in the energy range of 20 to 150 MeV. Details of the instrument response to solar γ-rays and neutrons are presented.

INTRODUCTION

COMPTEL, the Imaging Compton Telescope, has unique capabilities for measuring the flux and energy of both the solar γ-ray and neutron emissions. With its field-of-view (FOV) of about 60° for γ-rays and 90° for neutrons the Sun will often be in the γ-ray or neutron FOV when the Observatory is in the sunlit portion of the orbit. According to a recent viewing plan for Phase I of the mission, COMPTEL will have approximately 20% of the solar exposure of a dedicated solar observatory such as the Solar Maximum Mission. The Sun will be in the larger neutron FOV more frequently. In this paper we briefly describe the instrument and the detection technique and then present a preliminary response of COMPTEL to γ-rays and neutrons. Finally, we estimate the COMPTEL response to the γ-ray and neutron emissions from large solar flares.

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COMPTON TELESCOPE BASICS

A Compton telescope is a γ-ray detector in which the Compton scattering process is used to measure the photon's energy and incident direction. In this type of detector a γ-ray must scatter in two physically independent detecting elements or planes, nominally a forward and rearward detector. A precise time-of-flight (TOF) measurement establishes the general forward or backward direction of the scattered photon. For γ-rays the measured TOF must be consistent with the light travel time, in the process identifying scattered neutrons. Pulse shape discrimination techniques can further isolate the effects of neutrons. This delayed coincidence requirement efficiently suppresses contributions from internal radioactivity and backward scattered particles. These selection criteria can be adjusted to select neutrons, as opposed to photon events, as discussed below. Charged particles are normally rejected via thin active charged particle shields. The Compton scatter kinematics impose an additional geometrical constraint upon the scattering process using the energy deposits in the two detectors to provide the photon scatter angle as described below and illustrated in Fig. 1.

$$\phi = \cos^{-1}(1 - \varepsilon/E_2 + \varepsilon/(E_1 + E_2)) \tag{1}$$

Here, ε is the electron rest mass energy, E_1 is the energy deposit in the forward detector, E_2 is the energy deposit in the second or rearward detector and ϕ is the Compton scatter angle provided $E_1 + E_2$ is the full incident γ-ray energy. Although the constraints of coincidence, timing and inferred scatter angle greatly reduce the background contribution to the instrument count rate, they simultaneously reduce the detecting efficiency. Consequently, Compton telescopes are generally large in order to compensate for the reduced efficiency while retaining a high signal-to-noise ratio. Because of the large size, it is fortunate that Compton telescopes often have a large ratio of active to passive material, minimizing background generation. The necessity of collimation, it can be argued, is obviated by the inherent directionality of the TOF and scatter angle criteria, eliminating the mass associated with active or passive γ-ray shielding.

The basic scattering process for photons is illustrated in Fig. 1. The quantities that one measures are the location of the Compton scatter in the forward detector, the energy E_1 of the scattered electron, the location of the scatter in the rearward detector and the energy deposit E_2 in that detector. One computes from these interaction locations the direction of the scattered photon's velocity vector. From the energy deposits, one computes the scatter angle ϕ and the total γ-ray energy ($E_1 + E_2$). Without measuring the direction of the scattered electron in the forward detector, only the polar angle and not the azimuth angle of the scatter is known. The azimuth information is solely contained in the direction of the scattered electron in the forward detector; this direction is not measured in COMPTEL.

COMPTEL γ-RAY RESPONSE

COMPTEL, designed for the Gamma Ray Observatory, is a Compton telescope as described above (Schönfelder *et al.* 1991). It is the first Compton telescope to be placed on-orbit and will provide the opportunity to perform observations solar flares in addition to other cosmic sources. The mechanical design of COMPTEL is illustrated in Figure 1. An incoming γ-ray scatters off an electron in one of 7 D1 detectors and proceeds down to one of 14 D2 detectors scattering again. Such events constitute the ideal type of γ-ray interaction. The material in D1 is a liquid organic scintillator, NE213A, with the properties of low density and low Z (H/C ratio = 1.213). The material scatters both γ-rays and neutrons elastically, off atomic electrons and hydrogen nuclei, respectively. The detector is a fraction of a mean free path thick, meaning that the incident γ-ray (or neutron) can scatter in D1 and usually leave D1 without scattering again. For the case of small angle γ-ray scatters (< 10°), the incident γ-ray can deposit a large part of its energy in the D2 detector which is composed of NaI (high density, high Z).

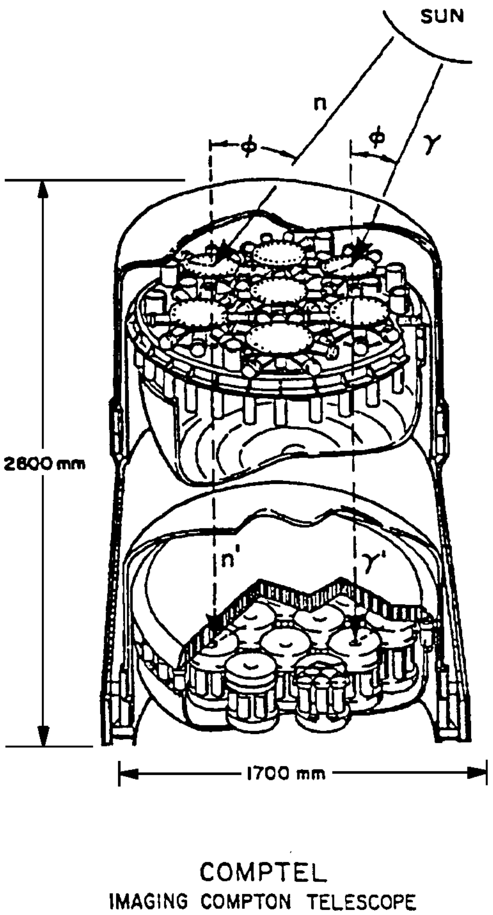

Figure 1.
Schematic of COMPTEL with typical γ-ray and neutron interactions.

The liquid organic scintillator in D1 (NE213A) possesses pulse shape discrimination properties, in that energetic protons produce light pulses with longer rise times than those of electrons (and other minimum ionizing particles). This capability allows for efficient identification of signals from recoil protons produced by fast neutrons elastically scattering off hydrogen in D1. Any reaction producing a recoil proton can be identified by these means, such as inelastic scattering of fast neutrons off carbon producing a γ-ray and either a knock-on proton or neutron (which can then elastically scatter off hydrogen). Pure γ-ray producing neutron reactions off carbon in D1 are also possible and represent an intrinsic background in both γ-ray and neutron measurements.

The D1 and D2 subsystems of the telescope are each completely surrounded by charged particle detectors (see Fig. 1). These 4 domes of plastic scintillator NE110 are 1.5 cm thick and do not significantly attenuate the incident γ-ray or neutron fluxes, yet are virtually 100% efficient in identifying charged cosmic rays. The charged particle shields and other intervening material will heavily attenuate the solar flare hard X-ray flux, minimizing pulse pile-up effects in the D1 and D2 detectors.

The incident photon direction is constrained to a cone mantle of half angle ϕ, a result of the azimuthal symmetry in the detection process. In order to translate this geometrical feature to the the coordinate system of the telescope we require knowledge of the positions of the γ-ray or neutron scatters in D1 and D2. This is accomplished not only by knowing in which detectors the scatters occurred, but also by locating an event within a detector by comparing the relative pulse heights of the attached photomultiplier tubes. This provides spatial information within the triggered detectors in D1 and D2.

For γ-rays, errors in the measured energy and scatter angle occur via uncertainties in the measured energies in D1 and D2 and uncertainties in the measured interaction positions in D1 and D2. Partial energy absorption in D2 (from an escaping γ-ray) yields a low value for the total γ-ray energy and a large value for the scatter angle ϕ.

The total geometrical area of the forward detector array D1 is approximately 4300 cm^2, while the effective area for γ-ray double scatters in the range of 1 to 10 MeV is < 40 cm^2. The spatial resolution (1 σ) in a D1 module (~ 1 MeV) is ~ 2 cm, while that in a D2 module is ~ 1 cm. Although a function of incident energy and angle, the energy resolution of the system for γ-rays is between 5 and 10% (Fig. 2).

COMPTEL as an imaging solar γ-ray telescope relies on the full energy deposit of the γ-ray to correctly estimate the scattering angle ϕ of the photon in the instrument. For a solar flare γ-ray interacting in COMPTEL, the inferred scatter angle ϕ about the vector of the scattered γ-ray must be such that the photon is assigned a solar origin as indicated schematically in Figure 1. Hence, we know that the photon deposited its full energy in the detector. The response of the telescope to such events is simple. The energy or pulse height distribution is basically Gaussian in shape with a heavily suppressed Compton tail at low energies. Since the solar γ-ray spectra are rich in lines from C, N, O, Ne, Mg etc., a simple instrumental response function will facilitate correct de-convolution of the pulse height spectra. The response of a telescope prototype to monoenergetic 1.375 and 2.75 MeV photons from a ^{24}Na source is shown in Figure 2.

The effective detector area of COMPTEL to 5 MeV solar photons incident at 30° is about 25 cm^2, decreasing to about 10 cm^2 at 1 MeV and 20 MeV (Schönfelder *et al.* 1991). For the solar γ-ray flare, which occurred on 1982 December 7, the average γ-ray flux > 1 MeV was about 1 photon cm^{-2} s^{-1}, including bremsstrahlung and nuclear emissions, over a period of ~ 1000 s (Vestrand *et al.* 1987). With COMPTEL's sensitive area this would result in a count rate of 25 s^{-1}, slightly exceeding the telemetry rate of COMPTEL of 20 s^{-1}. For a 1000 s event duration this yields ~ 20 000 counts for good spectroscopy statistics.

COMPTEL BURST MEASUREMENTS

The burst mode of the COMPTEL instrument can also be used to detect the first fast burst of solar γ-rays. The programmable Burst Spectrum Analyzer (BSA) continually integrates γ-ray spectra from two separate D2 detector modules in a background mode at a programmable cadence and integration time (nominally 30 s). One detector covers the energy interval from 0.1 to 1 MeV and the other the interval from 1 to 10 MeV. Each detector has an unobscured field-of-view of about 2.5 sr and an area of ~ 600 cm^2. Outside this field-of-view varying amounts of intervening material exist

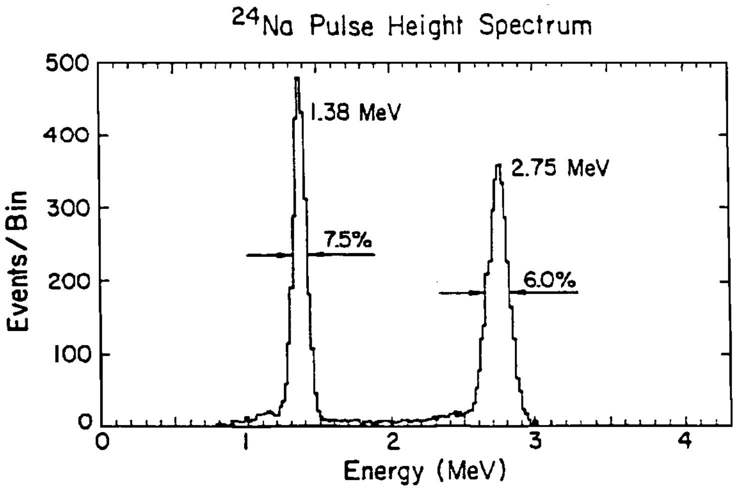

Figure 2.
The energy spectrum from a monoenergetic γ-ray source produced under the constraint that the γ-ray scatter angle ϕ be consistent with the source direction.

attenuating the solar γ-ray flux. The capabilities of COMPTEL for burst detection have been discussed by Winkler *et al.* (1986). When the burst system on COMPTEL receives a signal from the Burst and Transient Source Experiment (BATSE) (Fishman *et al.* 1989) indicating a burst of any origin, it starts accumulating spectra in these two modules at programmed time intervals, nominally every 2 s, for a total of six spectra, after which it switches to a so-called tail mode integration time of ~ 10 s. This fast accumulation rate provides information about the initial solar burst of γ-rays. These integration times are adjustable on-orbit, but only before the event. The evolution of both the bremsstrahlung and nuclear emission spectra is important in understanding the nature of the particle acceleration and transport processes. The earliest moments of a flare often carry the greatest information in terms of the relative timing of the two forms of γ-ray emission. Longer duration flares, such as those of 1982 December 7 and 1981 April 24 will be covered by the tail mode of the BSA in addition to the individual photon data in the telescope mode.

COMPTEL OPERATION DURING SOLAR FLARES

Within 5 s after the burst onset, the BATSE (Burst and Transient Source Experiment) instrument on the Gamma Ray Observatory sends a second signal to the On-Board Computer (OBC) if the burst originated from the general direction of the Sun (Fishman *et al.* 1989). Within the next two minutes, depending on the timing of the BATSE signal relative to the OBC telemetry frame, the OBC commands COMPTEL into a solar neutron mode for a time interval of 90 minutes or one orbit. COMPTEL still accumulates spectra in the two D2 burst detector modules, which collect burst spectra independent of instrument mode.

Double scatter telescope events are assigned a telemetry priority depending upon the measured event characteristics. During a solar flare, the event priority is determined primarily by the internal TOF, which separates γ-rays from non-relativistic neutrons. The priority γ1 is the highest priority, reserved for cosmic or solar γ-ray events, with other events, γ2 priority, (i.e. background γ-ray and neutron events) largely filling the remainder of the telemetry stream. After the onset of the γ-ray flare and before the instrument switches into the solar neutron mode, it remains in its primary cosmic γ-ray observing mode, collecting solar γ-rays in addition to extrasolar photons. In intense flares the solar flux will dominate all others. Upon the delayed command of the OBC, COMPTEL switches into the solar neutron mode. While the instrument is in the solar neutron mode $\gamma1$ (priority) events (solar and cosmic γ-rays) are still in the data stream, while the $\gamma2$ channel is modified so as to selectively record solar neutron events. Solar neutrons, $\gamma2$ events, are separated from the γ-rays by TOF. Pulse height requirements in D1 and D2 and Pulse Shape Discrimination (PSD) criteria in the D1 detectors are also employed to further enhance the neutron signature in the $\gamma2$ data channel. The delay in commanding COMPTEL into the solar neutron mode has no impact on the scientific content of the data. Solar neutrons < 150 MeV lag behind the initial γ-rays by up to 7 minutes, in which time COMPTEL is ready to measure and record the events.

COMPTEL NEUTRON RESPONSE

The ideal type of neutron interaction in COMPTEL occurs when the incoming neutron elastically scatters off a hydrogen nucleus in the D1 detector. The scattered neutron then proceeds to the D2 detector where it may interact, depositing some of its energy to produce a trigger signal as indicated in Figure 1. The energy of the incident neutron is computed by summing the proton recoil energy E_1 in the D1 detector with the energy of the scattered neutron E_s deduced from the TOF from the D1 to the D2 detector. The scatter angle for non-relativistic neutrons (< 150 MeV) can be computed by the formula:

$$\tan^2 \phi = E_1/E_s . \qquad (2)$$

As with γ-rays, neutrons can be traced backwards from D2 to D1 through the angle ϕ to a cone mantle restricting the incident direction to include the Sun. This is a geometrical constraint identical to that of the γ-ray measurements. The pulse shape from recoil protons is sufficient to reject more than 95% of electron-recoil events greater than about 1 MeV, the energy threshold in D1 for neutron detection. This method of detecting and measuring the neutrons is clean, in that a delayed coincident scatter with the correct pulse shape in D1 is required, yielding a large signal-to-noise ratio. Inelastic neutron reactions with carbon also occur in the liquid scintillator, particularly at energies greater than about 50 MeV. The carbon interactions in D1 often produce γ-rays, deuterons or alphas which can be identified. Typical problem reactions are

^{12}C(n,np)
^{12}C(n,2n)
^{12}C(n,n'γ)
^{12}C(n,n'3α)
^{12}C(n,n'pγ).

These reaction channels can be included to further increase the instrument response to neutrons. These interactions, however, are difficult to interpret because the lost energy (nuclear binding energy or escaping γ-rays) results in an inaccurate measures of E and ϕ. In the case of a solar neutron flare, identified by time, these events can be used to supplement the information obtained from clean elastic scatters.

With COMPTEL in the solar neutron mode, neutron interactions appear in the $\gamma2$ channel, covering the TOF interval from about 8 to 40 ns. The PSD and TOF criteria in this channel are such that solar neutrons incident on D1 in the energy range from about 10 MeV to 150 MeV are recorded. In this energy interval COMPTEL can observe neutrons from about 14.5 to 55 minutes after release from the Sun. This corresponds to a minimum observed delay time of 6 to 47 minutes after the onset of the γ-ray flash (assuming neutrons are not produced without accompanying γ-rays).

A prototype of COMPTEL (Science Model 3) consisting of two D1 and three D2 modules was exposed at the Indiana University Cyclotron Facility to calibrated pulsed neutron beams from 20 to 200 MeV incident at various angles with respect to the telescope axis. The resulting data were inspected to select events obeying the proper kinematic relationship for elastic scatters. The measured efficiencies of single D1/D2 module pairs (minitelescopes) are listed in Table 1 for various incident angles and energies. The resulting effective area of COMPTEL for neutrons incident at 29.2° is 12.1, 16.1 and 3.1 cm^2, where the calculated area is scaled up to the full COMPTEL instrument from the single minitelescope efficiencies in Table 1.

Table 1

Efficiencies for neutron detection with the constraint that the inffered scatter angle ϕ be consistent with neutron source direction.

	Energy (MeV)		
Angle	18.5	35.7	77.0
5.5°			6.7×10^{-5}
19.6°	2.9×10^{4}	4.4×10^{4}	
25.4°			7.6×10^{-5}
29.0°	3.1×10^{-4}	5.0×10^{-4}	
29.2°	2.1×10^{-4}	2.8×10^{-4}	5.4×10^{-5}
38.0°		1.2×10^{-4}	

Energy resolution figures are available for the analyzed Science Model 3 data. In Figure 3 are the measured energy spectra from monoenergetic neutron beams as indicated. Note the low energy tail in the 77 MeV data resulting from inelastic carbon reactions in D1. The prototype Science Model 3 was not tuned for precise location of neutron interactions within the individual detectors, so the acceptance angle windows are unusually wide (±10°), determined here by the physical size of the detectors rather than the spatial resolution of the detectors. The energy resolution is largely determined by the TOF measurement between D1 and D2. The pulse height or energy resolution in the scintillation measurement in D1 is generally negligible. There are three contributions to the energy resolution: the finite thickness and diameter of the two detectors creating an uncertainty in the path length over which the TOF is measured, the energy spread in the neutron beam due to the thickness of the target and the electronic TOF resolution, which for COMPTEL is 1.5 ns (FWHM). For the minitelescope D1/D2 pair at 29.2°, *for which there was no interaction location performed*, we expect from an error analysis energy resolutions (FWHM) of 17%, 15% and 18% for 18.5, 35.7 and 77.0 MeV, respectively. We measure 24%, 24% and 25% for those energies. For COMPTEL, in which the spatial resolutions are 2 and 1 cm for D1 and D2, respectively, we expect a greater rejection of spurious events by narrowing the scatter angle acceptance window from ± 10° to ± 2°. The discrepancy between the *a priori* estimate of the neutron energy uncertainty and that measured is not resolved pending re-examination of several instrumental gains and offsets.

An uncertainty (1 σ) of 8% (or 18% FWHM) in the measured energy of a 50 MeV solar neutron translates into an uncertainty of < 3 minutes in the production time of the neutron at the Sun. For solar flares which exhibit prolonged acceleration of protons on the order of 10 minutes (Ryan and Lee 1991) such the 1982 June 3 event (Forrest *et al.* 1985), this time resolution will aid in constructing a time dependent neutron production and, consequently, primary proton acceleration/precipitation spectrum.

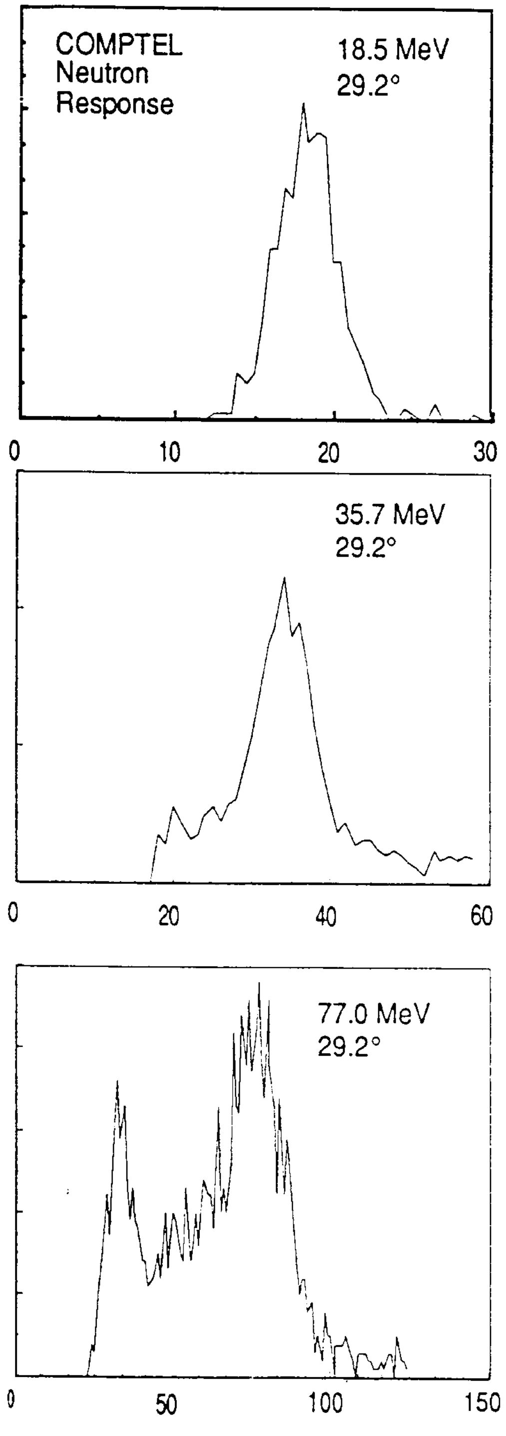

Figure 3
The energy spectrum from monoenergetic neutrons as indicated. Data are selected based on scattering kinematics consistent with the source direction.

We can use these extrapolated efficiencies to estimate the response of COMPTEL to the solar neutrons from a flare event such as that of 1982 June 3. The calculated neutron energy spectrum in total neutrons produced per MeV at the Sun as a function of energy according to Murphy *et al.* (1987), assuming that the neutrons are impulsively produced, is plotted in Figure 4. A power law in rigidity times an exponential in energy is assumed for the solar neutron production spectrum, i.e.

$$dN/dE = A\, p^{-5} \exp(-E/1000), \qquad (2)$$

where p is in Mv and E in MeV. The resulting neutron energy spectrum at the earth corrected for the neutron lifetime is shown in Figure 4. The energy range of COMPTEL for solar neutrons, as indicated by the heavy line from about 10 MeV to 200 MeV, covers the maximum in the neutron energy spectrum at earth. An event such as that of 1982 June 3 would have produced about 3300 clean neutron events below 100 MeV in COMPTEL over a time interval of about 40 minutes or an average event rate of $\leq 2\ s^{-1}$, within the telemetry bandwidth of γ_2 events. The count rate spectrum peaks in the range of 40 MeV where the neutron spectrum peaks as well as the instrument effective area. A statistically significant spectrum can be produced with such a large number of events. The background neutron event rate is difficult to estimate until it can be measured directly. However, we can generously take the event rate > 1 MeV in the D1 detector to be 1000 s^{-1} and that in D2 to be 2000 s^{-1} and with a coincidence window of 30 ns this yields an accidental event rate of 0.1 s^{-1}, a large fraction of which will be rejected when the scatter angle and pulse shape restrictions are applied.

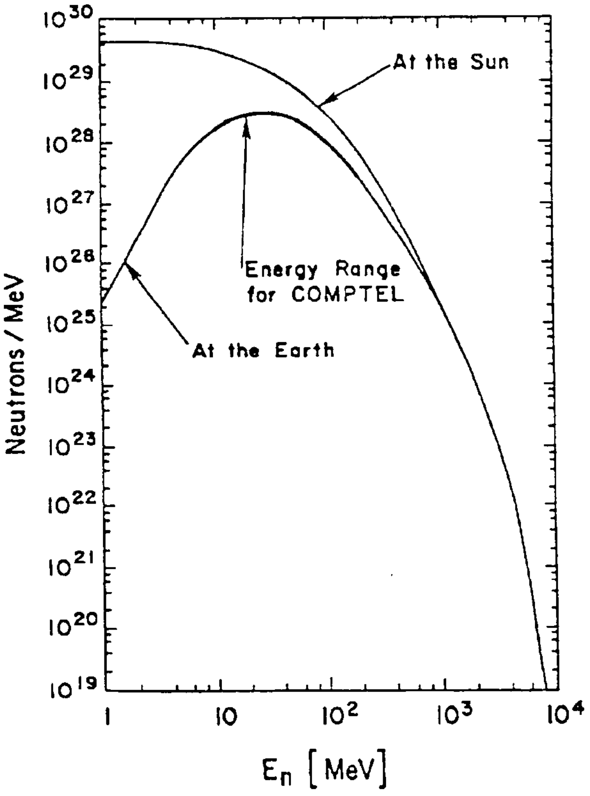

Figure 4
Neutron Production Spectrum from the 1982 June 3 solar flare (Murphy *et al.* 1987).

CONCLUSIONS

After April 1991, the projected launch date for GRO, while still on the elevated part of the solar cycle, we should expect a number of solar γ-ray events with emission of photons > 0.8 MeV. From February 1980 to December 1982 Rieger *et al.* (1983) found ~ 130 solar flares with emission > 0.3 MeV, of which 8 emitted > 10 MeV γ-rays. Two of these events emitted measurable neutrons > 50 MeV. Consequently, we should expect to find solar flares with both high energy γ-rays (> 1 MeV) and neutrons (> 10 MeV) present, since the energy threshold of COMPTEL for neutrons is much lower than that of the SMM detector and since the neutron response curve of COMPTEL is well-matched to the solar neutron energy spectrum at earth.

By combining the normal imaging capabilities of COMPTEL with its burst mode operation and solar neutron spectroscopic abilities, definitive information should be obtained about the spectral evolution of nucleonic and electronic processes in solar flares. Neutron energy measurements provide more precise and extensive data about proton acceleration. For the unusual solar flare occurring on the west limb of the Sun in which prompt, energetic solar protons (> 500 MeV), γ-rays and neutrons are observed and measured, we should be in a position to understand better the relative roles of stochastic and diffusive shock acceleration processes at the Sun.

REFERENCES

Fishman, G.J., C.A. Meegan, R.B. Wilson, W.S. Paciesas, T.A. Parnell, R.W. Austin, J.R. Rehage, J.L. Matteson, B.J. Teegarden, T.L. Cline, B.E. Schaefer, G.N. Pendleton, Jr. F.A. Berry, J.M. Horack, S.D. Storey, M.N. Brock, and J.P. Lastrade 1989, BATSE: The Burst and Transient Source Experiment on the Gamma Ray Observatory, Goddard Space Flight Center, Greenbelt, MD: NASA.

Forrest, D. J., W. T. Vestrand, E. L. Chupp, E. Rieger, J. Cooper, and G. Share 1985, *Proc. 19th Internat. Cosmic Ray Conf.*, **4** : 146-149.

Murphy, R. J., C.D. Dermer, and R. Ramaty 1987, *Ap. J.*, **316** : L41-56.

Rieger, E., C. Reppin, G. Kanbach, D. J. Forrest, E. L. Chupp, and G. H. Share 1983, *Proc. 18th Internat. Cosmic Ray Conf.*, **10** : 338.

Ryan, J.M., and M.A. Lee 1991, *Ap. J.*, **368** : 316-324.

Schoenfelder, V., K. Bennett, W. Collmar, A. Connors, A. Deerenberg, R. Diehl, J.W. den Herder, W. Hermsen, G.G. Lichti, J.A. Lockwood, J. Macri, M. McConnell, D. Morris, J. Ryan, G. Simpson, H. Steinle, A. Strong, B.N. Swanenburg, B.G. Taylor, M. Varendorff, C. de Vries, and C. Winkler 1991, The GRO-COMPTEL Mission: Instrument Description and Scientific Objectives, Erice, Sicily.

Vestrand, W.T., D.J. Forrest, E.L. Chupp, E. Rieger, and G.H. Share 1987, *Ap. J.*, **322** (2) : 1010-1027.

Winkler, C., V. Schönfelder, R. Diehl, G. Lichti, H. Steinle, B.N. Swanenburg, H. Aarts, A. Deerenberg, W. Hermsen, L. Lockwood, J. Ryan, G. Simpson, W.R. Webber, K. Bennett, A.V. Dordrecht, and B.G. Taylor 1986, *Adv. Space Res.*, **6** (4) : 113-117.