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COMPTEL Neutron Response at 17 MeV

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ABSTRACT

The COMPTEL instrument was exposed to 17 MeV d,t neutrons prior to launch. These data have been analyzed and are compared with Monte Carlo calculations using the MCNP(LANL) code. Energy and angular resolutions are compared and absolute efficiencies are calculated at 0 and 30 degrees incident angle. The COMPTEL neutron responses at 17 MeV and higher energies are needed to understand solar flare neutron data.

I. Introduction

The COMPTEL instrument on the Gamma Ray Observatory is sensitive to neutrons with energies above about 10 MeV. It has optimum sensitivity in the energy range expected for solar flare neutrons. These neutrons can be detected in the double scatter mode where the incident neutrons first elastically scatter from hydrogen in one of the 7 D1 liquid scintillator modules and then are detected in one of the 14 D2 NaI(Tℓ) scintillator modules. The neutron's incident energy and direction are determined in much the same way as they are for an incident gamma ray. The incident neutron energy, E_n, is the sum of the recoil proton energy loss in D1, E_p, and the scattered neutron energy, $E_{n'}$. This latter energy is determined from the time-of-flight from D1 to D2. The n-p scatter angle, θ_{np}, is calculated using $\tan(\theta_{np}) = E_p/E_{n'}$ (non-rel.). With the locations of the interactions in D1 and D2, the incident direction is determined to a cone in space containing the source direction (see Fig. 1).

The COMPTEL instrument is unique in that it can detect solar flare gamma rays and neutrons simultaneously and distinguish between these two different radiations. While the solar gamma ray arrival time histories duplicate their production time histories at the sun, this is not true for the neutrons which travel at different speeds. Thus, COMPTEL's independent determination of the neutron's energy also provides the time of production at the sun's surface.

COMPTEL's neutron response is complicated by the inclusion of neutron-carbon interactions in the D1 organic scintillator material (NE 213A). At neutron energies below 20 MeV, carbon elastic scattering can account for large direction changes for neutrons in D1 with minimal neutron energy loss. Above 20 MeV, inelastic carbon interactions which produce both a secondary charged particle and a neutron are important (e.g., C(n,n'p)B).

The pulse shape discrimination feature of COMPTEL's D1 scintillation detectors allows proton-producing events to be selected. The time-of-flight measurement selects events with neutrons moving from D1 to D2. These together with the requirement that the event cone include the solar direction should provide relatively clean selection criteria for solar neutron elastic n-p double scatter events.

Preliminary results will be presented here for COMPTEL's neutron response at 17 MeV. Calibration results are compared with Monte Carlo calculations.

II. Calibration Description

The complete COMPTEL instrument was extensively calibrated during the summer of 1987 at the GSF Van De Graaff accelerator facility at Neuherberg (Germany). As part of this calibration, the COMPTEL instrument was exposed to 17 MeV d,t neutrons. The calibration setup is shown in Figure 1. The telescope-target distance was 8.4 m. Data for nominal incident angles of 0° and 30° were obtained. Using a deuteron incident energy of 2.5 MeV, neutrons produced at 55.3° w.r.t. to the beam line have an energy of 17.2 MeV. The spread in neutron energy over the COMPTEL D1 area was 0.3 MeV.

Processed double scatter calibration event files consist of D1 and D2 interaction locations and pulse heights (in units of keV electron-equivalent energy loss), the D1 pulse shape parameter (PSD channel no.) and the D1-D2 time-of-flight (TOF channel no.). The separation of neutron and gamma ray events with time-of-flight (TOF) and pulse shape (PSD) is shown in the scatter plot in Figure 2. Only events with TOF > 170 are shown here. The forward gamma ray TOF peak is nominally at ch. 120. In our analysis of COMPTEL neutron data, only events with TOF > 200 and PSD > 100 are considered.

III. Monte Carlo Simulation

The simulation code MCNP (Forster et al. 1990 and references therein) -- Monte Carlo Neutron Photon -- is used to predict COMPTEL's neutron response. This code is a general-purpose continuous-energy Monte Carlo code developed as part of the Los Alamos Radiation Transport Code System. The physics of time-dependent neutron and photon transport and interactions are modeled in detail using the latest available cross-section data. Problems with neutrons, photons and electrons either as single particles or coupled particles can be calculated. Neutron cross-sections cover the energy range from 10^{-5} eV to 20 MeV while the range for photon transport is 1 keV to 100 MeV.

Another part of this transport code system is "LAHET" which is used with MCNP to extend the neutron range to in excess of 10 GeV. A third part of this system is "SABRINA" which is a graphics code to interactively set up three-dimensional models with a color display of geometries and particle tracks.

Currently, we are running MCNP with older neutron cross-section files which do not include Iodine-127. Barium-137 has been used instead along with Sodium-23 for the D2 NaI(Tℓ) scintillator material. New files available soon include iodine.

Table 1 lists the 1-sigma Gaussian resolutions which were incorporated into the analysis of simulated events.

Table 1. Simulation Resolutions (1 sigma)

D1 spatial: 2.5 cm	D1 Energy: 0.058 MeV at 1 MeV($E^{1/2}$)
D2 spatial: 2.5 cm	D2 Energy: 0.041 MeV at 1 MeV($E^{1/2}$)
Time of flight: 1 ns	

COMPTEL instrument electron-equivalent energy loss thresholds of 50 keV and 500 keV were imposed for D1 and D2, respectively. For D1 this corresponds to a 500 keV proton energy loss. At energies below 20 MeV, neutrons incident on the D2 NaI(Tℓ) modules produce a trigger almost exclusively by nuclear excitation followed by fast gamma emission (n,n'γ) and subsequent electron detection. Plural elastic scattering with the scintillator nuclei occurs as the neutron tends to bounce around the module. In general, more than one ionizing electron are produced. The interaction time and x,y location of the largest electron energy loss are used and the summed ionization energy loss in D2 is used for the threshold trigger. This extended time-of-flight produces a mean energy reduction of about 0.2 MeV for the scattered neutron. A few events (~8%) have energy reductions greater than 1 MeV. A maximum D2-D2 time-of-flight of 40.7 ns is used.

Our COMPTEL model includes the four anti-coincidence veto domes of plastic scintillator surrounding the D1 and D2 modules. With electron/proton energy loss thresholds of 250 keV/1 MeV, about 19% of neutron-induced double scatter events also trigger the veto domes for 20 MeV incident neutrons.

IV. Results

A. D1 Pulse Height Response to Protons

The D1 modules are calibrated for electron energy loss at various known gamma ray energies. It is well known that proton energy loss in organic scintillator material has reduced light output due to the much larger ionization energy loss (dE/dx) of stopping protons. This non-linear response has been measured for the liquid scintillator NE-213 by Cecil et al. (1979). The COMPTEL D1 material is NE-213A, an improved scintillator also with pulse shape discrimination properties.

For single elastic n,p scattering in the D1 modules, the recoil proton energy loss can be calculated directly from the difference of the known incident neutron energy, E_n, and the measured scattered neutron energy, $E_{n'}$, from time-of-flight. Figure 3 compares the electron equivalent energy losses determined from the measured pulse heights with the calculated recoil proton energies. The range of recoil proton energies allowed by the COMPTEL geometry for 30° incident neutrons is about 1-9 MeV.

The general agreement of the data with the relationship of Cecil et al. (1979) is shown in Figure 3. There is also considerable broadening due primarily to the uncertainty in time-of-flight distance resulting from the thicknesses of the D1 and D2 modules. Further analysis of calibration data is needed to confirm this agreement. For the remaining analyses below, the energy loss relationship of Cecil et al. will be used to interpret the pulse height in terms of proton energy loss.

B. COMPTEL Neutron Energy and Angular Resolutions

Both the 0° and 30° incident angle data sets have been analyzed to determine the energy and angular resolutions for 17 MeV neutrons. These results are directly compared with MCNP simulation results. Figure 4 shows the results for 30° incident angle. In Figure 4a, the solid curve represents the calculated n,p scatter angle distribution with only the previously discussed PSD (>100) and TOF (>200) cuts applied to the data. The large excess at 10-15° is due to gamma ray events with TOF and PSD values in the tails of the gamma ray PSD and TOF distributions which exceed the cuts. By requiring that the event cone for each event be within 3° of the true source (target) direction, this excess is eliminated. This is shown by the dashed curve in Figure 4a. Figure 4b gives the scatter angle distribution from the Monte Carlo simulation. Note the agreements in the maximum and minimum scatter angles and the general shape of the distributions in these two figures.

The COMPTEL energy resolution for 17 MeV neutrons is found from the energy distribution of those neutron events with event cones again within 3° of the true source direction. This is a realistic restriction to apply to solar neutron data when the sun is within COMPTEL's field-of-view. Figure 4c shows such a distribution for the calibration data with Figure 4d providing the simulation distribution. The measured peak energy for 17.2 MeV incident neutrons at 30° is 16.7 MeV with a FWHM of 2.6 MeV or 16% energy resolution. The Monte Carlo simulation does not include the 0.3 MeV actual incident energy variation discussed in Part II.

The angular resolution is measured by comparing the true or geometric scatter angle with the calculated scatter angle. In Figure 1 the ARM (angular resolution measurement) angle (θ_{np} - θ_g) is the angular distance between the event cone and the target direction measured from the D1 interaction. Figure 4e shows the ARM angle distribution for 17.2 MeV calibration neutrons incident at 30°. Only events with total energies within 2 MeV of the peak energy are included. The corresponding simulation ARM angle distribution is shown in Figure 4f. Table 2 summarizes the energy and angular distribution parameters for both 0° and 30° incident angles. Both calibration and simulation results are given.

Table 2. COMPTEL 17.2 MeV Neutron Energy and Angle Resolutions

Incident Angle	0°, Cal.	0°, Sim.	30°, Cal.	30°, Sim.
Peak Energy	17.0 MeV	17.0 MeV	16.7 MeV	17.1 MeV
ΔE, FWHM*	3.7 MeV (22%)	2.9 MeV (17%)	2.6 MeV (16%)	2.4 MeV (14%)
Peak ARM Angle	0.0°	+0.1°	-0.4°	+0.15°
Δθ, 1-sigma†	2.3°	2.2°	2.2°	2.2°

*Only events with event cones within 3° of the target direction are included.
†Only events with energies within 2 MeV of the peak energy are included.

There is excellent agreement between the predicted and measured angular resolutions. Thus, at energies below 20 MeV, 1-sigma angular resolutions of 2.2-2.3° can be expected with negligible systematic effects.

Two discrepancies in the comparison of energy distribution parameters are evident. At 30°, the calibration peak energy is approximately 0.5 MeV below the nominal 17.2 MeV value and at 0°, the calibration energy distribution full-width is broader than expected by about 0.8 MeV. The sources of these differences are not understood at present. A 0.2 MeV decrease can be explained as discussed in Part III.

C. Efficiencies and Effective Areas at 17 MeV

Figures 5 and 6 present the COMPTEL calculated absolute detection efficiencies and effective areas for 17.2 MeV neutrons incident at 0° to 45° w.r.t. the telescope zenith direction. For the Monte Carlo simulation calculations, parallel beams of incident neutrons were used, as were D1 proton energy thresholds of 500 keV and D2 energy thresholds of 500 keV (electron loss). In these simulations, no special restrictions were placed on the energy or ARM angle measurements. Neutron time-of-flights were cut off at 40.7 ns and induced gamma ray and backscatter neutron events were eliminated. The effective area is calculated from the efficiency, the D1 area and the incident angle. A maximum efficiency of 0.26% corresponding to an effective area of 11.5 cm^2 occurs at 0° incident angle. The efficiency decreases to 0.15% at 45° with an effective area of about 5 cm^2. As yet, a comparison of calculated and measured efficiencies has not been made. Beam monitor data for the 17 MeV runs will be analyzed in the near future.

V. Future Analyses

Additional neutron calibration data with a science model of COMPTEL are available and will be analyzed. The COMPTEL science model, consisting of two D1 modules and three D2 modules, was exposed to neutrons at four nominal energies from 20 to 135 MeV. The results of these data need to be compared critically with the simulation results of MCNP and LAHET. As more confidence in MCNP's ability to model the neutron response of COMPTEL over the full range of neutron energies expected from solar flares is gained, MCNP can be used as a data analysis tool for interpreting individual solar neutron events.

VI. Acknowledgements

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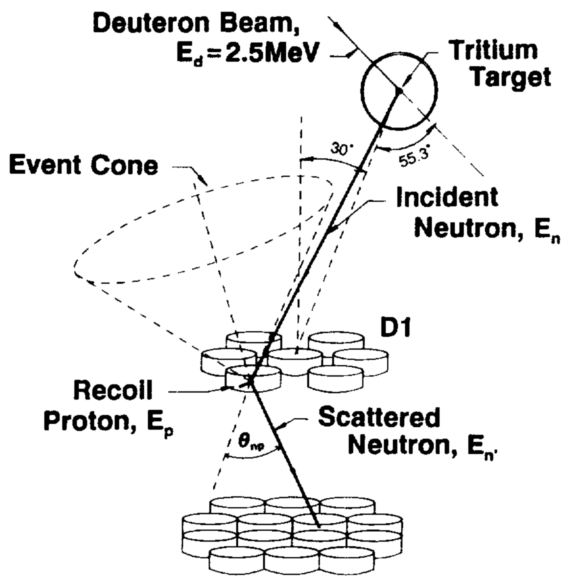

Fig. 1 Calibration Setup

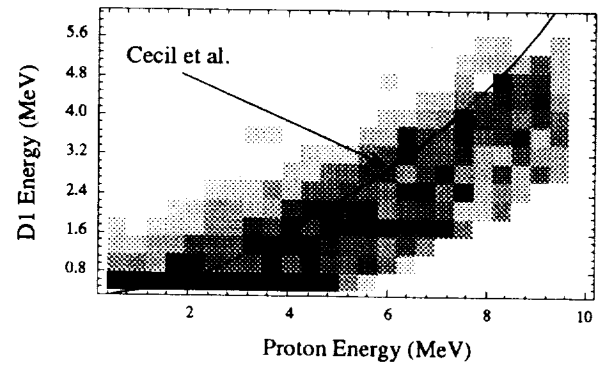

Fig. 3 Electron equivalent energy loss versus proton energy for 17 MeV incident neutrons at 30°.

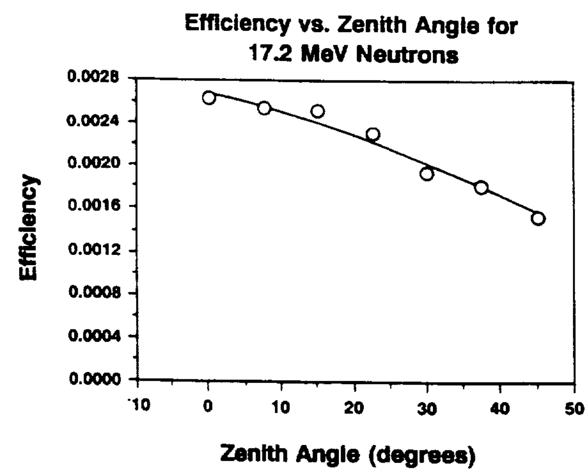

Fig. 5 COMPTEL Monte Carlo Efficiencies at 17.1 MeV as a function of incident angle.

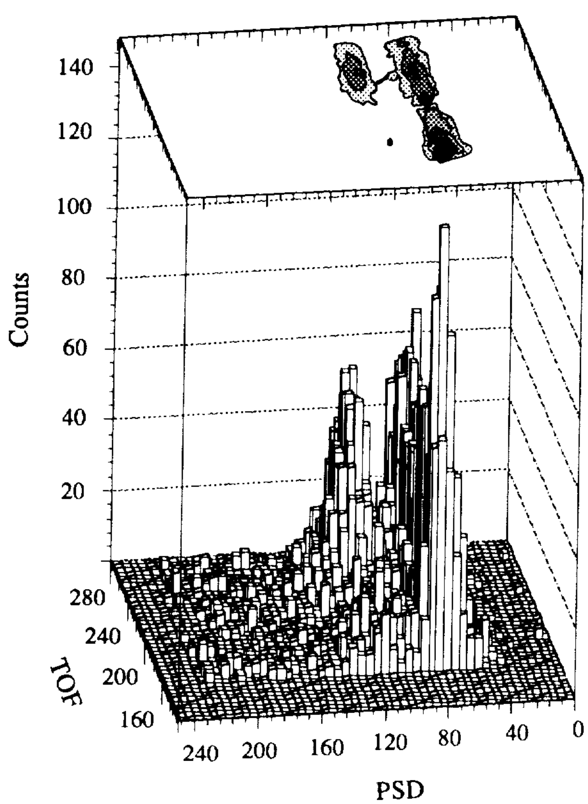

Fig. 2 Counts versus PSD and TOF parameters for 17 MeV neutrons incident at 30°.

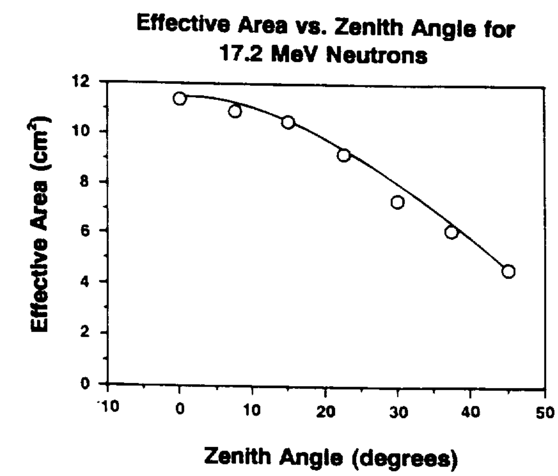

Fig. 6 COMPTEL Monte Carlo Effective Areas at 17.2 MeV as a function of incident angle.

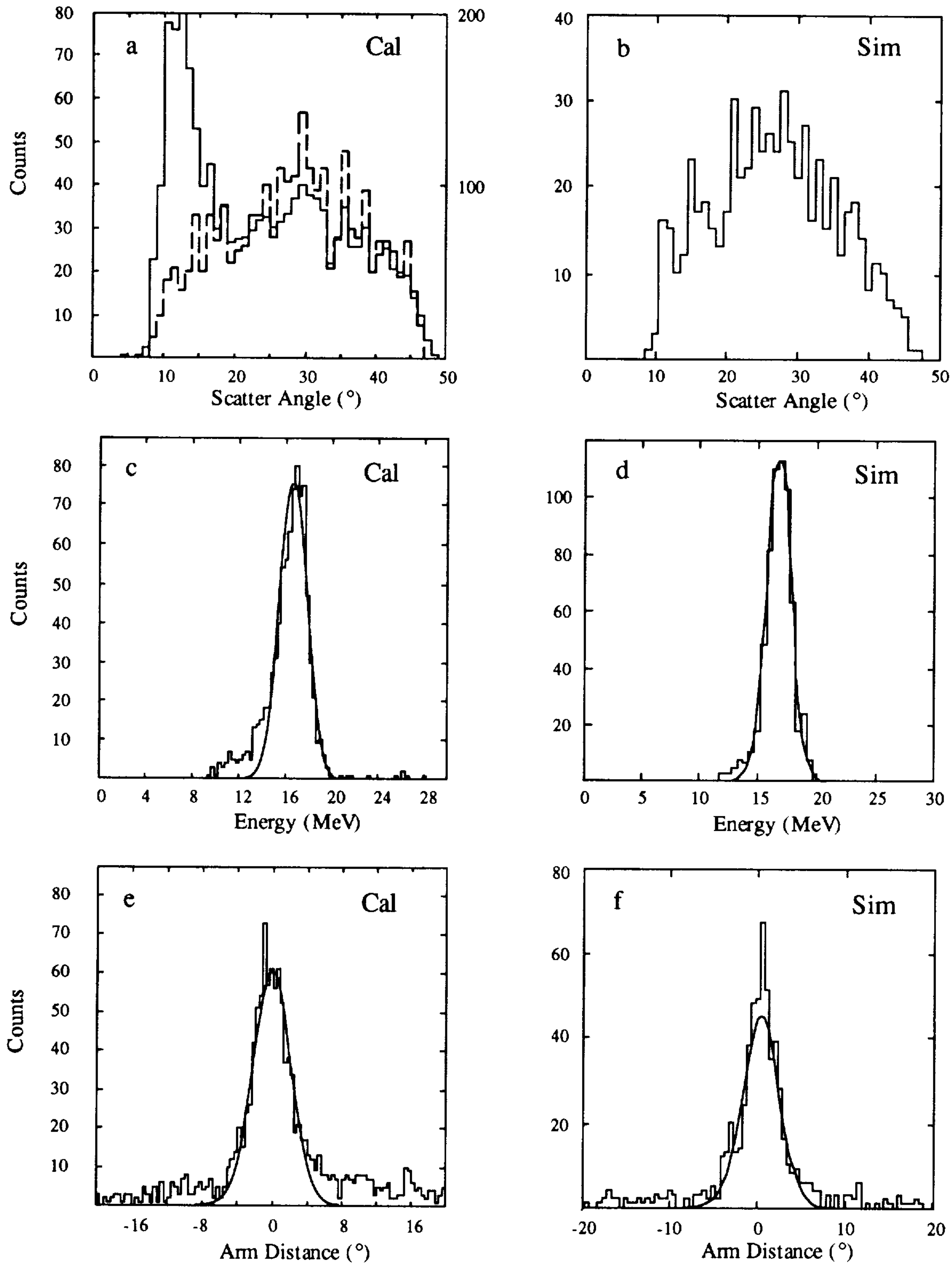

Fig. 4 Scatter angle, energy and angular distributions for 17 MeV incident neutrons at 30°. See text for discussion.