A COMPTON SCATTER ATTENUATION GAMMA RAY SPECTROMETER

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A Compton scatter attenuation gamma ray spectrometer conceptual design is discussed for performing gamma spectral measurements in monodirectional gamma fields from 10^2 R hr^{-1} to 10^6 R hr^{-1}. Selectable Compton targets are used to scatter gamma photons onto an otherwise heavily shielded detector with changeable scattering efficiencies such that the count rate is maintained between 500 and 10^4 sec^{-1}. Use of two sum-Compton coincident detectors, one for energies up to 1.5 MeV and the other for 600 keV to 10 MeV, will allow good peak to tail pulse height ratios to be obtained over the entire spectrum and reduces the neutron recoil background rate.

INTRODUCTION

The NASA, Marshall Space Flight Center desires to measure the gamma radiation energy spectrum created by the radiation leakage from a space nuclear propulsion reactor. The gamma ray spectrometer is to be physically located at the top of a liquid hydrogen tank with the propulsion reactor at the bottom of the tank. The purpose of the spectral and intensity measurements is to provide an accurate aid in the design of minimal weight gamma radiation shielding for various radiation sensitive payloads.

Conventional gamma ray spectrometers cannot be used for this application due to the high gamma flux intensity. The presence of a high neutron flux, composed of liquid hydrogen temperature thermal neutrons in addition to the hard neutron flux further complicates the gamma spectral measurement.

This paper briefly outlines a solution for these measurement problems resulting from a recent study contract[1]. The technique is a Compton scatter attenuation gamma ray spectrometer which basically consists of scattering a portion of the gamma flux onto an otherwise heavily shielded gamma spectral detector. The scattered gamma radiation energy spectrum may be related to the incident spectrum by the well known Compton energy shift relationship through the fixed angle of scatter. This technique may only be employed for a highly directional gamma flux, as exampled by the proposed application.

REQUIREMENTS AND PROBLEMS

The gamma field is expected to be approximately 100 R hr^{-1} with the LH$_2$ tank full and the reactor at full power and increasing to 5×10^5 R hr^{-1} as the tank is emptied. This is equivalent to a photon flux approximating 5×10^7 cm^{-2} sec^{-1} to 2×10^{11} cm^{-2} sec^{-1}. The pulse height analysis rate for single events is limited and the gamma interaction cross sections are such that directly exposed spectral detectors would need to be smaller than 10^{-3} grams, which is much smaller than the range of the gamma recoil electrons. Therefore, directly exposed spectral detectors are prohibited.

Another NASA requirement is that separate spectral measurements be obtained in each five second interval of the short operating time, and the data must also have reasonable statistical accuracy. To meet this requirement, the analysis counting rate must always be high, and as the gamma intensity will vary by more than three orders of magnitude, we must decrease the detection efficiency as the gamma intensity increases.

The neutron environment is not severe until the last few seconds of power as the tank is emptied. At 30 seconds prior to an empty tank, the fast neutron flux is 10^5 n cm^{-2} sec^{-1} but rapidly increases to 2×10^8 n cm^{-2} sec^{-1} as the tank is emptied prior to reactor shutdown. One consequence of the neutron environment is that small gamma spectral detectors must be employed to reduce the background rate from this source.

The gamma radiation energy range of interest is 50 keV to 10 MeV with the highest energy radiation caused by neutron scatter and capture. It is expected that the gamma spectrum intensity will vary by over four orders of magnitude from the low to high energy end of the spectrum. Thus, it is difficult to get statistical accuracy at the upper end of the spectrum during a five second interval because only 10^{-4} of the photons are above 5 MeV and the count rate and count time period are limited.

The only feasible way that we have found for performing these measurements is with a Compton scatter attenuation gamma ray spectrometer with a variable detection efficiency.

CONCEPTUAL DESIGN

Figure 1 indicates the design concept of Compton scatter attenuation. A collimator, with its axis pointing directly toward the reactor, is used to define the area of a gamma beam which strikes successive Compton scattering targets for the separate spectral detectors. The targets are located on the two wheels which are synchronized with a common axis drive. Three Compton targets are on each wheel and each can be rotated into the gamma beam by the stepping motor geared to the axis drive. A position with no target also exists, so that occasional detector background measure-

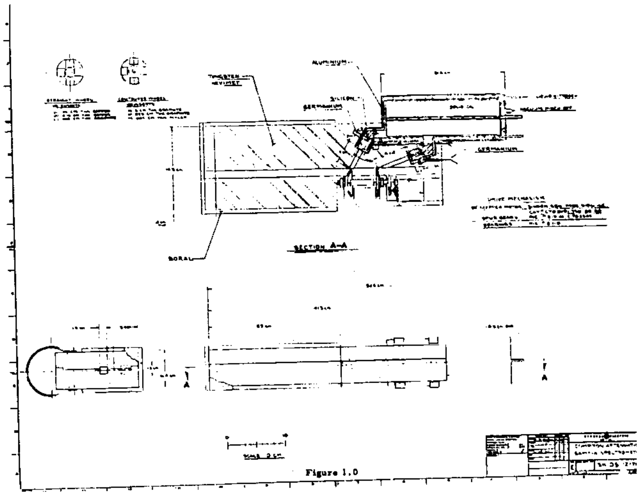

Figure 1.0

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ments can be made for subtraction from the measured data. The lower wheel has carbon targets and radiation scattered through a 60 degree angle is incident on the first detector, which is designed for low gamma ray energy spectroscopy. The second wheel contains copper targets and the radiation is scattered through 20° to the second detector designed for high energy gamma ray spectroscopy. A short lead plug is inserted to remove the bulk of the low energy photons toward the second spectral detector.

We have calculated the spectral effects of non-Compton interactions in the carbon target, which include coherent scattering and pair production. These reactions are very minimal, and although coherent scattering increases the total scattering cross section at 50 keV somewhat, the energy difference to the incoherent Compton scatter is small. Coherent scattering decreases rapidly with increasing gamma energy. Pair production is high in the copper targets, which are used to increase the relative sensitivity of the second spectrometry but the 511 keV annihilation photons are below the useful range of this spectrometer and will be rejected electronically.

The Compton targets on a single wheel vary in area density by factors of 20, i.e., the carbon targets are 1.1 grams cm^{-2}, .055 grams cm^{-2}, and .0027 grams cm^{-2}. Switching from a target to the next lightest, will decrease the overall detection efficiency by a factor of 20, and for a given target the count rate will vary only by a factor of 20, and will be between 500 sec^{-1} to 10^4 sec^{-1}. The maximum counting and analysis rate is determined by inefficient sum-Compton spectrometers used as detectors, where coincident events are required between the coaxial detectors, and the singles count rate will exceed 2 x 10^5 sec^{-1} for 10^4 sec^{-1} coincident rate, and this singles rate is expected to tax the electronic circuitry, particularly the random coincidence rate and the system energy resolution. It is this singles rate that limits the coincident count rate of the system.

The tungsten shielding is a shadow shield for both neutron and gamma radiation. Photons scattered from adjacent side materials will not exceed 0.5 MeV for 90° scattering, and are more readily absorbed by the tungsten than the directly incident photons which include higher energies. Backscatter photons are even less energetic. Even so, the side shield dimensions may need to be increased beyond those shown, if massive scattering objects are close to the spectrometer.

The shield should produce a signal to background rate of 20:1 for the worst condition which is with the smallest Compton targets in view. The background rate was computed for gamma leakage through the shield interacting with the detectors and for fast neutrons producing recoil events within the detectors. Calculations using fast neutron removal cross sections from ORNL, show that the fast neutron flux is attenuated by a factor of 100 by this shield. Although the neutron radiation is not severe until the last few seconds of the anticipated measurement, it is this time period that contributes to the total gamma dose. Gamma radiation from inelastic scattering by neutrons in the tungsten is an additional source of background, but this effect is small compared to the neutron recoil interactions within the detectors. A boral shield will be used to reduce the thermal neutron flux, being almost totally opaque to the low temperature neutrons.

Two spectral detector systems are required to obtain better statistical accuracy for the high energy portion of the spectrum and additionally, because it is difficult to design small sum-Compton spectrometers with response down to 50 keV which are also capable of a response to 10 MeV. To see 50 keV, the central detector must be of a low Z material, such as silicon or glass, so that the scattered photon can escape to the surrounding secondary detector. But these materials have more energetic neutron recoil events than the heavier detector materials, such as germanium or CsI(Na), and their size must therefore be more limited. On the other hand, the range of gamma recoil electrons is approximately 0.5 grams per MeV, and thus a long and heavy detector is needed to detect most of the high energy photons. We solve this dilemma by using two spectral detectors, and we limit the photon energy incident on the low Z detector by having a 60° angle of scatter from the carbon targets on the first wheel.

Figure 2 shows the Compton energy shift relationships for various scattering angles θ. Note that for a 60° angle of scatter, the scattered energy never exceeds 1 MeV. As our expected detector peak to tail ratio is almost unity at 1 MeV, and increases for lower energies, the pulse height data for the low energy spectrometer, can be directly related to the incident spectrum by the relationship[2]

$$E_o = E' \; 1 + \alpha (\cos - \cos \theta) \qquad (1)$$

where E_o and E' are the incident and scattered photon energies, α is the incident energy in relativistic units, and θ is the angle of scatter.

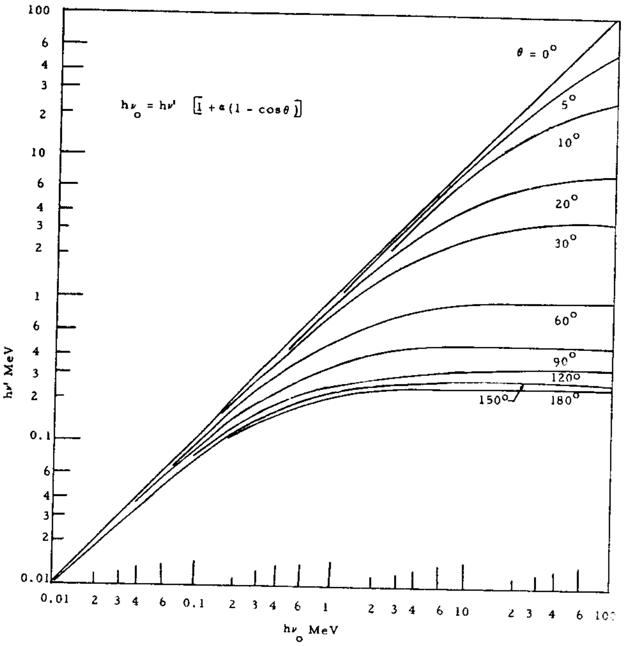


Figure 2.0. The Scattered Photon Energy $h\nu'$ as a Function of Incident Energy $h\nu_o$ and Scattering Angle θ

The low energy spectrometer would be useful for incident energies from 50 keV to 1.5 MeV corresponding to 45 keV to 600 keV for the scattered and detected radiation. Note that the energy width per channel of a pulse height analyzer is not constant due to the nonlinearity of the Compton energy shift.

As the peak to tail ratio is expected to be high, 4:1 at 600 keV and up to 60:1 at 50 keV, the data is directly reducible to a spectrum without resorting to the mathematical detector response unfolding techniques commonly used for single detector pulse height spectra. The differential Compton scatter cross section, at θ = 60°, decreases with increasing photon energies, and therefore the wide angle scattering reduces the number as well as the energy of the high energy photons.

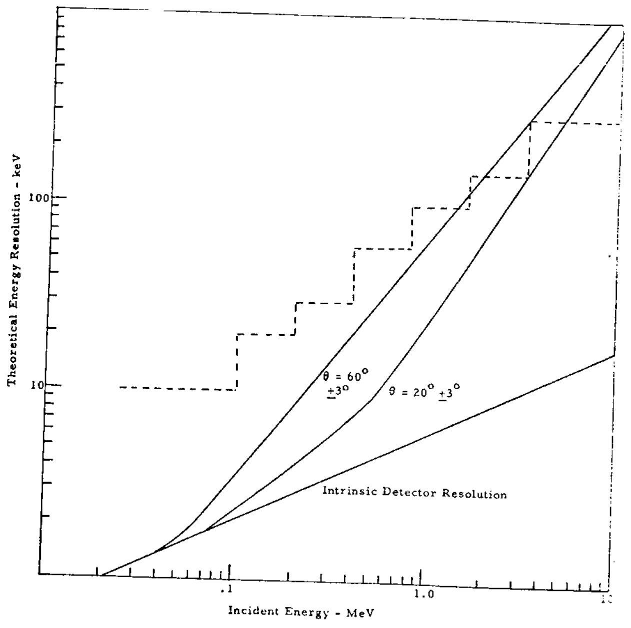
The high energy specrometer will see radiation scattered through 20°. It is expected to collect data for incident energies from 600 keV to 10 MeV. A short lead filter between the Compton target and the detector will remove most of the low energy photons and attenuate the high energy flux a moderate amount. Without the lead filter, 63% of the photons would be below 600 keV, and with the filter, only 11% of the filtered spectrum is expected to be below 600 keV, and this includes annihilation photons generated in the filter and Compton targets. Therefore, a more efficient detector may be used to increase the counting rate for the higher energy photons, and yet not be swamped with a multitude of low energy photons. This will result in a better statistical accuracy for the high energy portion of the spectrum.

The energy resolution of a Compton scatter attenuation spectrometer suffers from the nonlinear energy shift relationship. The energy resolution, ΔE_o of the incident radiation, approximates

$$\Delta E_o \cong \Delta E' \; 1 + \alpha \; (1 - \cos \theta)] + \alpha E' \sin \theta d \theta \quad (2)$$

where $\Delta E'$ is the instrumental system energy resolution. The first term on the right is the instrumental energy resolution multiplied by the energy shift relationship. The second term results from the finite scattering angle, and is the limiting factor for the higher photon energies. The expected energy resolution is shown in Figure 3 as computed from equation (2). We also show the expected detector system resolution for fair semiconductor detectors. The horizontal dashed lines represent the NASA requirements for energy resolution.

Figure 3.0 θ = 60° Low Energy Spectrometer
θ = 20° High Energy Spectrometer



Small sum-Compton detector systems are planned for the spectrometer because this type of detector gives higher peak to tail ratios than any other type of small detector. The detected signal pulses will approach total absorption, and therefore little data reduction will be necessary to obtain the incident gamma spectrum. The alternate choice of using a single small detector and mathematically unfolding the pulse height distribution with matrices of the detector response function, is not as satisfying. In addition, the coincidence requirements for forming the sum-Compton events reduces the background due to neutron recoil events significantly.

Peak to tail ratios exceeding 100:1 have been reported[3] for various sum-Compton spectrometers. These designs were rather inefficient, i.e., only a small fraction of the incident photons results in coincident sum events, and the detectors were too large for the present purpose. We have concluded that at least the order of four percent of the photons interacting in the center detector must result in Compton events simultaneously detected in the surrounding detector, to achieve a high count rate capability without an unduly high random coincident rate.

In addition to the random coincident pulses which result in false signals, there exists a random sum rate. The latter rate is the effect of an additional event occurring in either detector during the slow coincident time period of summing, in addition to the true Compton event. These type events add to the energy of the detected event and are largely due to neutron interactions within the detectors during the last few seconds of the measurement. We have studied these effects and concluded that they are not serious for the study of environmental conditions and the proposed design, but experimental measurements should be performed to substantiate these conclusions.

The high energy sum-Compton spectrometer will additionally detect pair events created in the center detector in which either or both of the annihilation photons are recorded by the secondary detector. These events increase the detection efficiency at the higher energies of the spectrum. The peak to tail ratio for high energy photons is approximately unity, but most of the tail distribution lies relatively close to the peak energy, and in effect, deteriorates the energy resolution by broadening the peak distribution.

The solid state detectors envisioned in Figure 1 are not within the present state-of-the-art. Lithium drifting is apt to penetrate the small junctions. It is anticipated that small coaxial intrinsic germanium[4] and silicon detectors will be within the state-of-the-art within two years. For the present, experimental studies can proceed using glass scintillators for the silicon detector and CsI(Na) scintillators for the germanium detectors. The major performance difference should be in a degraded energy resolution for the completed spectrometer.

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