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PARTICLE TRANSPORT SIMULATION FOR SPACEBORNE, NaI GAMMA-RAY SPECTROMETERS

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SUMMARY

Radioactivity induced in detectors by protons and secondary neutrons limits the sensitivity of spaceborne gamma-ray spectrometers. Three dimensional Monte Carlo transport codes have been employed to simulate particle transport of cosmic rays and inner-belt protons in various representations of the Gamma Ray Observatory Spacecraft and the Oriented Scintillation Spectrometer Experiment. Results are used to accurately quantify the contributions to the radioactive background, assess shielding options and examine the effect of detector and spacecraft orientation in anisotropic trapped proton fluxes.

PARTICLE TRANSPORT SIMULATION FOR SPACEBORNE, NaI GAMMA-RAY SPECTROMETERS

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Abstract

Radioactivity induced in detectors by protons and secondary neutrons limits the sensitivity of spaceborne gamma-ray spectrometers. Three dimensional Monte Carlo transport codes have been employed to simulate particle transport of cosmic rays and inner-belt protons in various representations of the Gamma Ray Observatory Spacecraft and the Oriented Scintillation Spectrometer Experiment. Results are used to accurately quantify the contributions to the radioactive background, assess shielding options and examine the effect of detector and spacecraft orientation in anisotropic trapped proton fluxes.

Introduction

Radioactivity induced in scintillation detectors by cosmic rays, trapped protons and secondary neutrons produces an important source of background in spaceborne gamma-ray spectrometers[1]. For the early detectors, which employed relatively lightweight crystals of NaI and CsI (a few pounds) on modestly sized spacecraft (a few hundred pounds), typical particle pathlengths through the spacecraft and detector material were significantly less than the nuclear interaction length and the direct spallation interactions of primary particles sufficed to explain the observed radioactivity[1]. For the next generation of instruments to be carried on the Gamma Ray Observatory individual detector masses of order 2 tons are to be carried on a 15 ton spacecraft. Typical particle pathlengths exceed the nuclear interaction length and the consequent importance of secondary particles requires the application of particle transport codes. In a previous paper[2] 1-D transport calculations, which employed the ANISN[3] neutron code in spherical geometry, were used to assess the importance of secondary neutron capture on NaI and explore the efficacy of ^{6}LiH shield layers around the central NaI elements. Such layers were in fact shown to be counterproductive and this result was confirmed by preliminary results from a 3-D simulation of trapped proton transport in a more representative geometry[4]. In the current paper the full 3-D simulation is applied to a number of detector and spacecraft configurations in order to assess the dependence of the various background components on spacecraft and detector geometries and particle anisotropies.

Components of the Calculation

The Transport Suite

The codes used in this study all employ Monte Carlo techniques and include the High Energy Transport Code (HETC)[5] for protons and energetic hadrons and the MORSE[6] code for neutrons of less than 15 MeV. HETC is a nucleon/meson transport code which uses an intranuclear cascade and evaporation model[7] to simulate the

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nuclear interactions. MORSE is a coupled neutron/gamma ray code which utilises multigroup scattering and absorption cross-section data. It is used here to transport neutrons over the energy range from 15 MeV down to thermal energies using the neutron source generated by HETC. These codes share a common combinatorial geometry package. Other codes used to predict spallation product yields, time variations in induced radioactivity and energy-loss spectra for decay products are as discussed in Ref 1.

Detector and Spacecraft Geometry

The detectors and spacecraft under study are representations of the Oriented Scintillation Spectrometer Experiment (OSSE)[8] to be carried on the Gamma Ray Observatory. The OSSE detector employs four identical telescopes, each of which comprise a 13 inch diameter central NaI/CsI phoswich (a phosphor sandwich with a 4 inch thickness of NaI plus 3 inches of CsI and utilising the different pulse shapes in the two materials to veto events arriving from the rear), provided with an active NaI shield of about 3 inch thickness and a passive slat collimator of tungsten to give an opening angle of $5^{\circ} \times 11^{\circ}$. The telescopes are orientable through about 192° in pairs. The combinatorial geometry representation is illustrated in Figure 1. For simplicity the tungsten collimator is represented by a diffuse mass of lower density having the same total mass as the actual slat arrangement. The ^{6}LiH layer around the inner phoswich was given a thickness of 0.3 cm to represent the ^{6}LiF impregnated silicone actually incorporated in the instrument. This material was incorporated in order to reduce the influence of thermal neutrons arising from hydrazine tanks and plastic scintillators carried on the spacecraft. In certain simulations this thickness has been increased up to 5 cm to investigate the efficacy in reducing the more energetic neutrons from the spacecraft and outer NaI shield. Such increased thicknesses proved to be counterproductive in this case[4]. For certain simulations adjacent spacecraft material was represented by 10 cm of aluminium on two sides as in Figure 1. In other cases an isolated telescope was studied and in further cases a diffuse aluminium model of the spacecraft was employed (Figure 2). Intercomparison of these cases enables consideration of the relative importance of secondaries arising from the detector, local material and spacecraft.

Proton Fluxes

The incident trapped proton and cosmic ray fluxes and their spectra are those predicted for a 28.5°, 450 km orbit in 1991. As discussed in Ref 4, trapped protons have a characteristic energy of 100 MeV and probably do not exceed 600 MeV, while the majority of cosmic ray interactions arise from protons in the energy range from 6 to 30 GeV. The exact flux of trapped protons experienced in the South Atlantic Anomaly remains in some doubt, in part due to uncertainties in the models and in part due to debate as to the correct procedures for incorporating the influence of the time varying geomagnetic field. In the light of this debate Stassinopoulos[9] has recently revised the GRO proton fluence estimates and uses two alternative approaches to arrive at integral daily fluences in excess of 100 MeV of 3.6×10^{5} and 7.1×10^{5} cm^{-2}. In this paper we therefore use a value of 5×10^{5} with an uncertainty factor of two. This fluence is a factor of three lower than the value used in Ref 4. For simplicity isotropic incidence has been used in most cases. However use of these 3-D codes enables the influence of alternative distributions to be studied. Such effects are likely to be more important for trapped protons as they are highly anistropic and also less penetrating than cosmic rays. Recent studies of Space Station shielding have led to reconsideration of the spatial distribution of South Atlantic Anomaly protons[10]. Using this work proton distributions have been generated as illustrated in Figure 3, which shows that, in the SAA, protons are close to their mirror point and have pitch angles close to 90°. There is a further East-West anisotropy which increases with energy and is due to the removal of particles by the atmosphere.

Results

Sample results obtained to date are presented in Tables 1 and 2 for isotropic trapped protons and cosmic rays respectively for the geometries discussed above. The 1-D case is that studied in Refs 2 and 4 but using the revised trapped proton estimate, and in all cases the nominal shielding thickness of 0.3 cm of ^{6}LiH is used. It can be seen that results are in generally good agreement between the 1-D studies and the 3-D study on the isolated detector, the latter case tending to be higher by up to a factor of 2. This is presumably due to the more accurate treatment of the cascades to include tertiary and higher order products. Analysis shows that the production of particle cascades enhances the spallation background over that due to primaries by up to a factor of 3 for trapped protons and up to a factor of 13 for cosmic rays. The additional production of ^{128}I increases the overall background enhancement factors to 4.7 and 19.0 respectively. Comparison of the rates between the various geometries indicates that the presence of other detectors and spacecraft material has a net shielding benefit for trapped protons but has a deleterious effect for cosmic rays. This is due to the greater penetration and higher multiplicities for the production of secondaries of the more energetic cosmic rays.

Using the rates from the last rows of each table the best estimate of the spectra of the radioactive background components has been revised and results are presented in figures 4 and 5. The lower estimate for the SAA proton fluence and the higher multiplicities for cosmic ray effects raise the relative importance of the cosmic ray components compared with the estimates of Ref 2.

It can be seen that the production of ^{128}I by neutron capture provides a significant component of the background. Use of Monte Carlo codes enables neutron tagging to ascertain the origin of the neutrons which eventually capture in the central NaI element. Results are presented in Table 3 and confirm that the majority of captures in fact arise from neutrons originating in the same detector. Furthermore, within a detector the majority of captures in the central NaI are due to neutrons generated in the surrounding materials, primarily the massive NaI shield. This implies that any neutron shielding strategy must aim to shield the central NaI from the remainder of the detector structure. However attempts to use thermalising absorbers have appeared counterproductive[3]. This is confirmed in Figure 6 which presents the influence of varying the amount of ^{6}LiH shielding upon ^{128}I production rates in the central NaI crystal for the trapped proton case for all the simulations and geometries. The deleterious influence of thermalising absorber on the ^{128}I component is confirmed. This is more marked when there is a large source of neutrons as is the case for both the 1-D study, when the detector was allowed to grow with increased ^{6}LiH thickness, and the full spacecraft simulation. The effect of an alternative neutron shield location has also been examined. Naively it might be supposed that positioning an ^{6}LiH shield midway in the outer NaI shield could provide some advantage as it could then thermalise and absorb neutrons from the outermost annulus of NaI while the thermalised neutrons escaping would in part be removed by the inner annulus before entering the central NaI. Such a design would be more likely to be effective for the trapped proton source as in this case the neutron production is more biased towards the outside. Hence a simulation has been performed incorporating a 2 cm ^{6}LiH layer at the expense of the central 2 cm of the outer NaI sheild. Results for neutron capture and spallation are in fact not significantly different (7% enhanced) from the case for zero neutron shield. Thus use of ^{6}LiH shielding is not a promising approach for current sizes of detector. However it should be noted that the spacecraft model contained no thermalising materials. If the external neutron source has a thermal component it is possible that small thicknesses could have a net benefit against this component of the background.

Preliminary investigations have been made of the influence of detector orientation and particle anisotropies. Reorientation of the detectors with respect to the spacecraft within an isotropic flux gives variations which are currently not statistically significant and at present can be sized at less than 15%. However use of the trapped proton anisotropies of Fig 3 as input to the simulations indicates that activation of the central crystal can vary by about a factor of 2.3 between what are presumed to be the best (spacecraft to the West of the detectors) and worst (spacecraft to the South of the detectors, detectors pointing West) cases (Fig 7). Activation of the tungsten collimator is a factor of 4 higher for the worst case. Hence trapped proton effects could be diminished somewhat by appropriate orientation during South Atlantic Anomaly traversals. Further studies are needed using a more accurate representation of the collimator and covering a wider range of orientations while taking account of the mission constraints in order to determine the exact improvement that is possible.

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TABLE 1

TRAPPED PROTON EFFECTS

Daily trapped proton fluence = 5.0×10^5 cm^{-2}, Ep > 100 MeV

Configuration	Mean Production Rates s^{-1} in Central NaI		
	Neutrons	Spallation	^{128}I
1-D isolated	1119	267	205
3-D isolated	2033	552	266
3-D 4 detectors + 10 cm Al	1235	367	222
3-D 4 detectors + spacecraft	1038	378	248

TABLE 2

COSMIC RAY EFFECTS

Average Cosmic ray flux = 0.16 cm^{-2} s^{-1}, Ep > 100 MeV

Configuration	Mean Production Rates s^{-1} in Central NaI		
	Neutrons	Spallation	^{128}I
1-D isolated	1421	122	132
3-D isolated	1409	313	122
3-D 4 detectors + spacecraft	1690	330	161

TABLE 3

ORIGIN OF CAPTURED NEUTRONS

Proton Source	Fraction of Total Captures in Single Detector by Neutrons from:		
	1 Same Detector	2 Other Detectors	3 Spacecraft
Inner Belt	0.73	0.12	0.15
Cosmic Rays	0.81	0.13	0.06

Proton Source	For '1' above Fraction of Captures in Central NaI by Neutrons from:			
	Central NaI	CsI	W	Outer NaI
Inner Belt	0.16	0.24	0.16	0.44
Cosmic Ray	0.37	0.13	0.23	0.27

THE COMBINATORIAL GEOMETRY USED IN THE 3-D MODEL

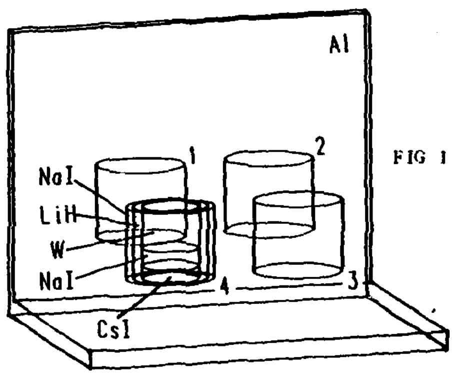


FIG 1

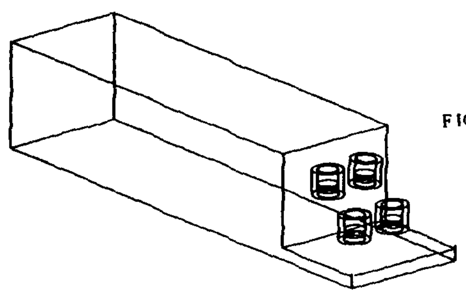
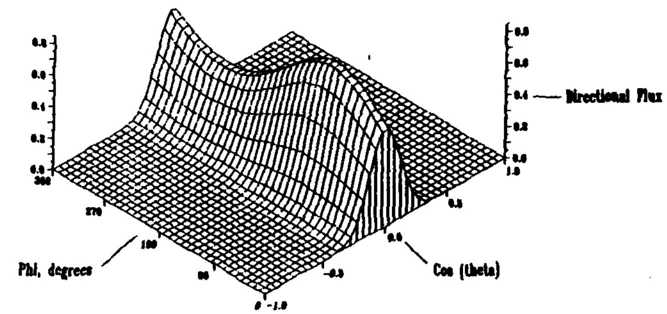


FIG 2

Spacecraft Geometry used to Simulate OSSE (Big Block)

TRAPPED PROTON ANISOTROPY AT 20 MeV



TRAPPED PROTON ANISOTROPY AT 600 MeV

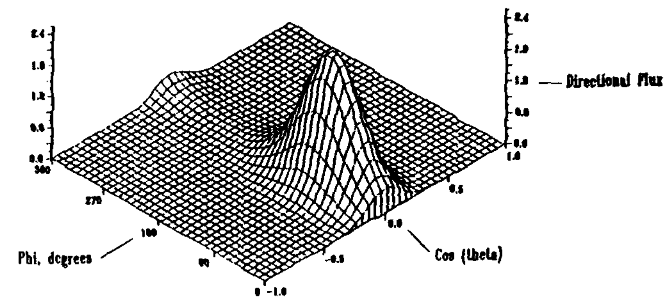


Fig 3 Proton directional flux distributions for the SAA show a narrow Gaussian in $\cos\theta$, where θ is the pitch angle, and a preferential flux of protons travelling geomagnetically eastwards ($\phi = 90^{\circ}$), particularly at high energies.

Figs 1-3

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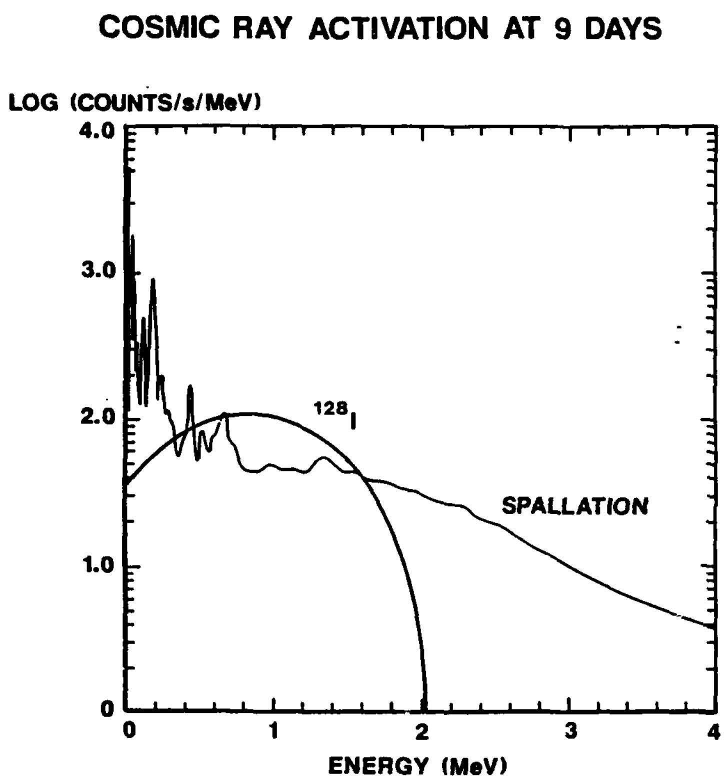

Fig 4 Energy-loss spectra are compared for radioactivity induced by spallation and neutron capture in the central NaI crystal due to interactions with cosmic rays for 9 days in orbit at 450 km, 28.5. Results are from the full 3-D spacecraft plus detector simulation.

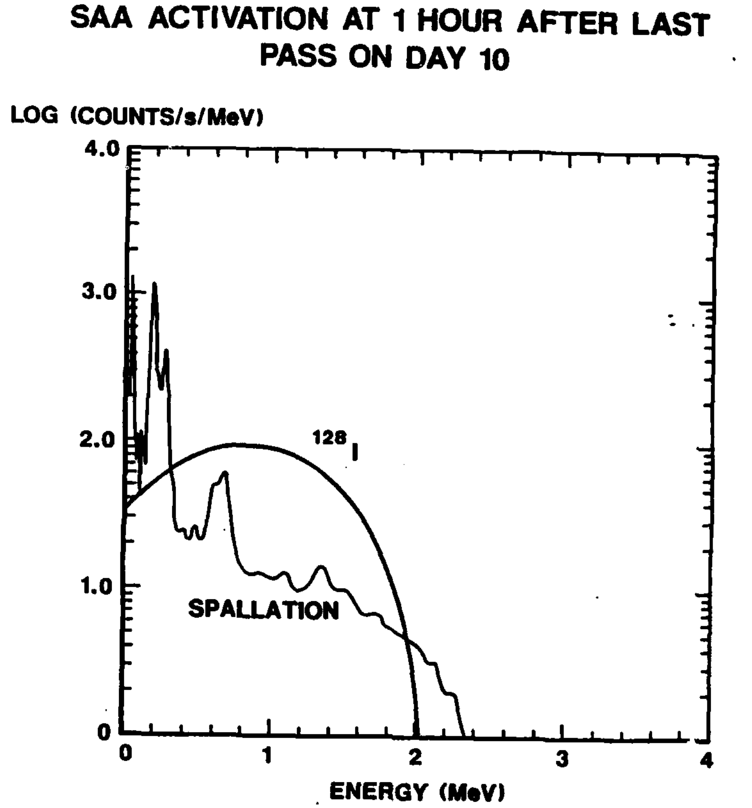

Fig 5 A comparison similar to Fig 4 is made for radioactivity induced by inner-belt protons, taking levels appropriate to 1 hour after the last significant SAA pass on day 10. Full 3-D simulation of spacecraft plus detector is used with isotropic trapped proton fluxes at the revised intensity.

Figs 4&5

NEUTRON CAPTURES ON IODINE IN INNER SODIUM IODIDE ZONE COMPARISON OF THE FOUR ILLUSTRATED GEOMETRIES; TRAPPED PROTON SOURCE

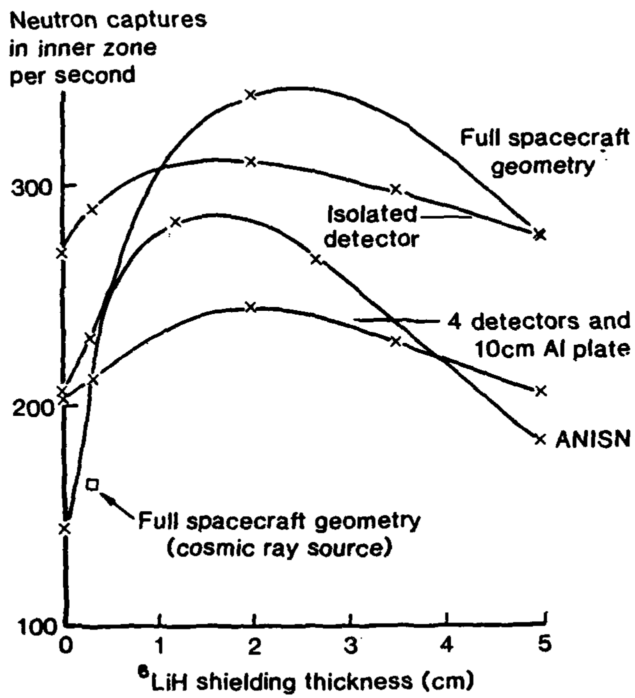

FIG 6

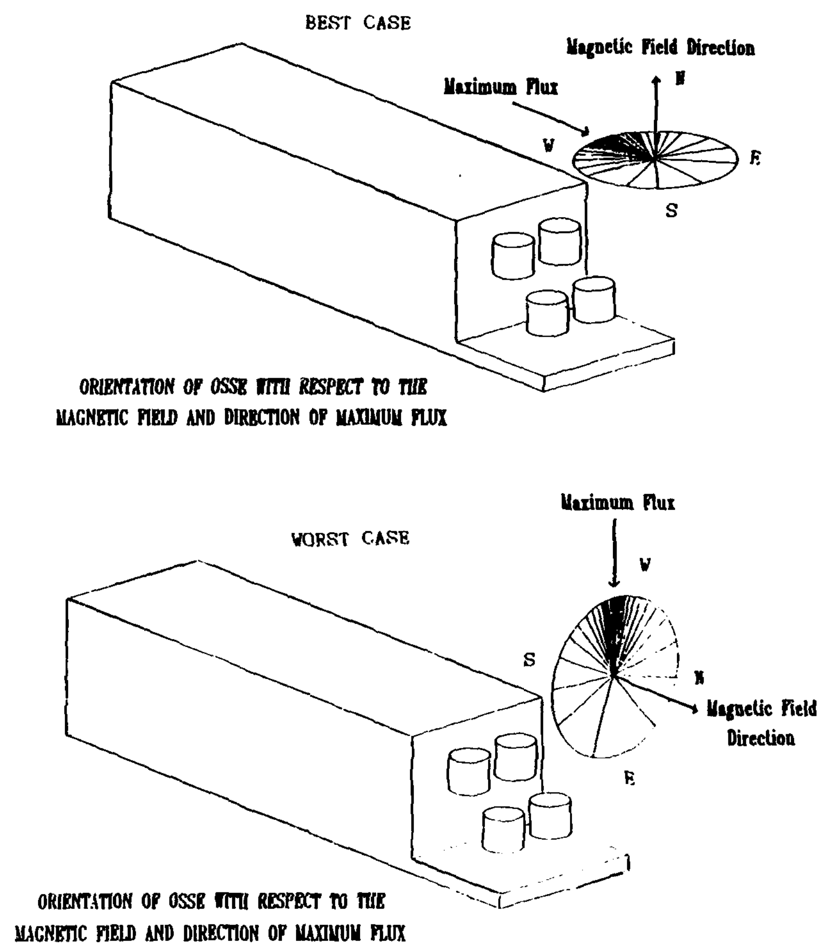

Fig 7 Supposed best and worst case orientations with respect to the geomagnetic field and the direction of maximum trapped proton fluxes.

Figs 6&7

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17. Abstract

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