PERFORMANCE OF AN INTEGRAL SPECTROMETER MODEL

P. Jean[1], J.E. Naya[2,3], P. von Ballmoos[1], G. Vedrenne[1], B. Teegarden[1,2]

[1]Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, BP 4346, 31029 Toulouse Cedex, France

[2]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

[3]Universities Space Research Association, 7501 Forbes Blvd. 206, Seabrook, MD 20706-2253, USA

ABSTRACT

Model calculations for the future spectrometer SPI (SPectrometer INTEGRAL) are presented: the sensitivity for narrow lines is based on estimates of the background level and the detection efficiency. The instrumental background rates (continuum and lines) are explained as a sum of various components that depend on cosmic-ray intensity and spectrometer characteristics (e.g. mass distribution around the Ge detectors, passive material, characteristics of the detection system and background reduction techniques). Extended background calculations have been performed both with Monte-Carlo simulations and using empirical, semi-empirical and calculated neutron and proton cross-sections. In order to improve the INTEGRAL spectrometer sensitivity several designs and background reduction techniques (shield thickness, pulse shape discrimination, active or passive coded mask, enriched or natural Ge detectors) have been compared for an instrument with a fixed detector volume.

Keywords: Nuclear astrophysics; INTEGRAL spectrometer; Instrumental background

1. INTRODUCTION

High-resolution spectroscopy provides the most direct means for studying radioactivity and excited nuclei in astrophysical sources. Because of the opacity of the atmosphere to high energy photons, the observation of astrophysical γ-ray sources has to be performed either at the top of the atmosphere or in space. In both environments, the spectrometers are exposed to high-energy radiations, inducing background that limits the instrument sensitivity. Previous studies (Gehrels (1985), Dean et al. (1991), Gehrels (1992), Naya et al. (1996)) have led to an appreciable understanding of the complex multicomponent background but have shown also several inherent limitations for its suppression. In this paper, background estimations for the future spectrometer SPI (SPectrometer INTEGRAL) are presented.

SPI is the high-energy resolution Ge spectrometer ($\Delta E/E \approx 0.2\%$ at 1 MeV) of the future INTEGRAL observatory. It is made of 19 detectors with a total area of 500 cm^2. It will be able to perform images with an angular resolution of $<3°$ by using a coded aperture system made of tungsten elements. Its goal is the observation of astrophysical γ-ray lines in the 20 keV-8 MeV energy range. For a detailed description of the spectrometer see Mandrou et al. (1996) elsewhere in this proceeding. In the present work, the optimization of the performance of SPI is presented. In Section 2., the origin and the components of noise in space-borne Ge spectrometers are listed and estimated. In Section 3, background reduction techniques are proposed and the predicted sensitivity is calculated for one SPI configuration.

2. THE INSTRUMENTAL BACKGROUND

2.1. The cosmic-ray particles as source of background

Under space conditions, the satellite and the instruments aboard will be irradiated by high-energy particles (p^+, e^-, γ) leading to background events in the Ge detection plane produced by interactions of primary or secondary particles. The sources and the physical processes that induce noise are multiple and complex. In order to estimate the background for a given spectrometer design, the noise is understood as the sum of several components depending on both the instrument characteristics (nature and thickness of the shield, nature of the detector, field-of-view) and the physical processes at the origin of background events. Since INTEGRAL will be in a high-altitude orbit, the background due to atmospheric γ-ray's and n are insignificant, so they are ignored.

2.2. The continuum background components

- Aperture flux: The photons that enter through the spectrometer aperture do not come only from the observed sources but also from the "cosmic diffuse γ-ray emission". This denomination is historic, the physical origin of these aperture γ, truly diffuse or composed of multiple individual sources, is unknown. The aperture flux component depends mainly on the size of the field-of-view.

- Internal detector continuum background: Primary and secondary hadrons created by inelastic interactions of cosmic-ray p^+ with the material of the instrument induce radioactive isotopes in the Ge detectors. Since the lifetimes of their decay are much longer than the anticoincidence times ($\approx \mu$s), the emitted particles (β^-, β^+, γ) produce signals that are not vetoed by the shield. They deposit a part or their total energy in the detector leading to a background event. Three β decay sub-components are distinguished. The first one is the "β^- localized". It occurs when the daughter nuclide is in a (meta)stable state. The second sub-component is the "β^- non localized" for which the daughter nuclide is in an excited state. The signal is produced by both the electron and the deexcitation γ. The third sub-component is called "β^+ decays". In this case, two 511 keV photons from the e^+ annihilation are involved in the detection. The yield of radioactive decays depends on: the isotopic composition of the detector, the p^+ flux irradiating the spacecraft and the mass distribution around the Ge detectors.

- Shield leakage: This background is due to γ detected in the Ge that come from outside the spectrometer field of view through the shield without depositing enough energy to trigger it. This component depends on the nature and the thickness of the shield, and the threshold value of its electronics.

- Elastic neutron scattering: Secondary n produced in the spacecraft may interact via elastic scattering with Ge nuclei. The signal is due to the energy deposited by the recoil nucleus. Consequently, this process is prompt and only those neutrons that do not trigger the shield while entering or leaving the spectrometer contribute to the background.

- Photons induced in the mask: Prompt interactions of cosmic-ray particles with the mask material generate γ's via the decay of π^0 in hadronic cascades induced by p^+ and via bremsstrahlung induced by e^-. The secondary γ's emitted in these processes may escape from the mask and deposit their energies in the detection plane. This component depends on the solid angle of the coded aperture system as seen from the detector and also on the distance between the mask and the active shield material. Indeed, primary and secondary particules induced in cascades can trigger the anticoincidence system if the latter is close enough from the mask.

2.3. 511 keV background line

The 511 keV background line is due to the annihilation of positrons induced by β^+ decays and pair creation in the material of the spectrometer. Active materials (detectors, anticoincidence system) should not produce detectable annihilation photons since the positrons deposit their kinetic energy in it. The total 511 keV background line is assumed to be the sum of three components depending on the location of the positron annihilation. (1) The passive material close to the detection plane emits 511 keV photons following the annihilation of β^+ particles. (2) e^+ are induced by the prompt interaction of particles (p^+, e^-, γ) in the coded mask and by the β^+ decays. (3) The annihilation photons emitted outside the spectrometer by the spacecraft may traverse the shield and deposit the totality of their energies in the detectors.

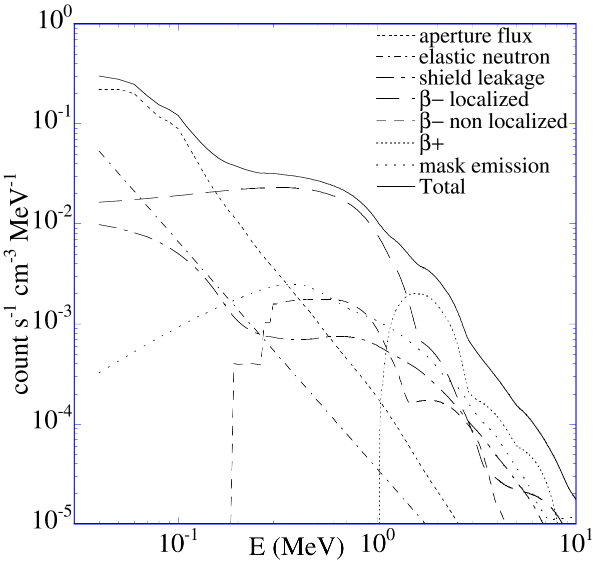

Figure 1: Predicted background spectrum of SPI with 5.5 cm of BGO. The various components are shown separately. Background reduction due to PSD is not shown.

2.4. Background estimation for SPI

The different background components have been estimated using both Monte-Carlo simulations using the code GEANT of CERN (Centre Européen de Recherche Nucléaire), semi-empirical and calculated cross-sections. A more detailed description of the calculations is reported in Jean et al. (1996). Figure 1 shows the predicted continuum background spectrum for a SPI model with 5.5 cm of BGO and a shield threshold of 80 keV. Below 0.2 MeV, the major component is the aperture flux. The localized β^- decay dominates significantly the total background between 0.2 MeV and 1 MeV. Above 1 MeV, the spectrum results in the sum of β^+ and β^- decays, shield leakage and mask emission components. The background rate at 511 keV is estimated to be 3.3 10^{-4} counts cm^{-3} s^{-1} for the model of SPI with 8 kg of passive material (Be, Al, Cu, Fe) inside the shield. 64% of intensity in the line is due to the mask emission. The background model does not include the effect of instrumental background lines (and their Compton tails). They are presently being studied. However, the rate induced by radioactive γ-ray lines in the mask has been estimated to be insignificant.

3. BACKGROUND REDUCTION

Background reduction techniques should suppress background events as efficiently as possible without much degrading the γ detection efficiency. Previous studies (Gehrels (1985), Barthelmy et al. (1994), Slassi (1996)) on background in Ge spectrometer have led to various techniques for its reduction. Since internal β decays dominate the background in balloon borne Ge spectrometers at 0.2-2 MeV range, a specific effort has been made in order to reduce their effect. In this section several methods to reduce the noise of SPI are presented and analysed.

3.1. The Pulse Shape Discrimination

In the 0.2-1 MeV energy range, the localized β^- decays dominate the total background. The energy of the β particles is deposited locally while the γ-rays mostly loose their energy by multiple Compton scattering in the detectors. Since the shape of the current pulses will be different for localized and non-localized events, it is possible to distinguish the photons from the localized β decays by a pulse shape analysis. Recent developments (Slassi (1996)) have shown the validity of this background reduction technique. Calculations show that, at 0.5 MeV, 99% of the localized β^- decay are expected to be rejected reducing by a factor of 6 the total background of SPI. However, at this energy, 20% of source photons are identified as noise event, decreasing the efficiency by a factor 0.8. Nevertheless, the use of PSD provides a gain of a factor 2 in sensitivity at 0.5 MeV.

3.2. ^{70}Ge enriched detectors

In order to reduce the β^- decays, detectors made of Ge isotopes have been proposed and manufactured. The use of ^{70}Ge enriched detectors has shown to reduce the radioactive nuclei decaying via β^- and improve the sensitivity in the 0.2-1 MeV range (Barthelmy et al. (1994)). Nevertheless, such isotopically enriched detectors provide a higher β^+ decay yield enhancing the background above 2 MeV (Naya et al. (1996)). Consequently, they have not been chosen for the INTEGRAL spectrometer because: (1) the background rate would be a factor 2 greater than with natural Ge at 2 MeV, and (2) the use of the PSD already allows to reduce significantly the localized β^- decay component.

3.3. Gamma-ray lines signature

The internal β^+ decay is the most important component above 1.2 MeV. The signal is due to the energy deposited by both the e^+ and the two γ produced by its annihilation. One or both 511 keV photons may escape the Ge detector of origin and deposit their total energy in the adjacent detectors. In this case, one or two 511 keV events will be registered in coincidence with the detector in which the β^+ decay occurs. Monte Carlo simulations show that an event selection with this profile allows the rejection of 26% of the β^+ decays. However, this selection of multiple detector events with 511 keV signature must be applied below 3 MeV where the γ's from the source do not interact significantly with the Ge by pair production, or else the efficiency would be damaged at higher energies.

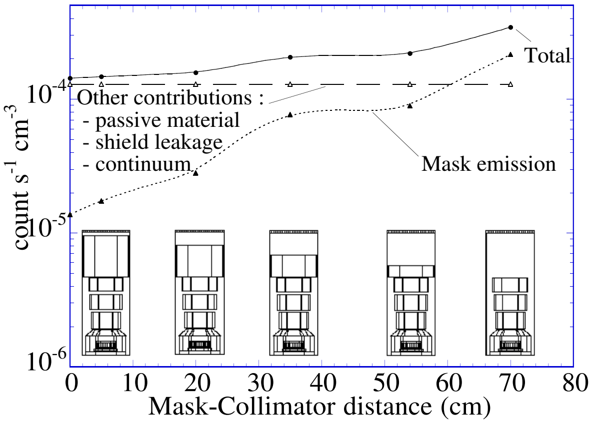

Figure 2: Total 511 keV line intensity as a function of the distance between the mask and the active BGO collimator. The mask emission at 511 keV is shown apart from the other components. Background reduction due to PSD is not shown.

3.4. Plastic scintillator

All prompt events induced in the mask by charged cosmic-ray particles passing through the BGO are rejected. Hence, the coded aperture effective emissivity depends strongly on the proximity of the active material. The effect should be roughly proportional to the solid angle under which the anticoincidence is seen from the mask. Figure 2 shows the intensity of the total 511 keV background as a function of the distance between the mask and an additional BGO collimator ring. The intensity increases with increasing distance. If it is not possible to add a BGO collimator up to the mask, a plastic scintillator set underneath the W would detect charged particles and reject a large proportion of prompt events induced by cosmic ray p^+ and e^-. Monte Carlo simulations show that the use of a plastic scintillator improves the sensitivity by a factor 1.4 at 511 keV including the transparency of a 5 mm thick plastic scintillator ($\approx$90%).

3.5. Background variation with the shield thickness

The noise components that vary with the shield thickness are the β decays and the shield leakage. Indeed, the more massive the anticoincidence system, the more secondary n's are induced by cosmic-ray p^+ interaction in the shield. Thus, a thicker shield increases the production of radioactive isotopes in all the material inside the shield. The β decay yield should decrease if the BGO thickness is reduced, but the shield leakage component would then be increased. It therefore becomes necessary to optimize the shield thickness for a minimal background rate. Calculations have been performed for shield thicknesses in the 1 to 6 cm range and assuming that the PSD and a plastic scintillator set under the mask are used (Fig 3a and b). The minimal continuum and 511

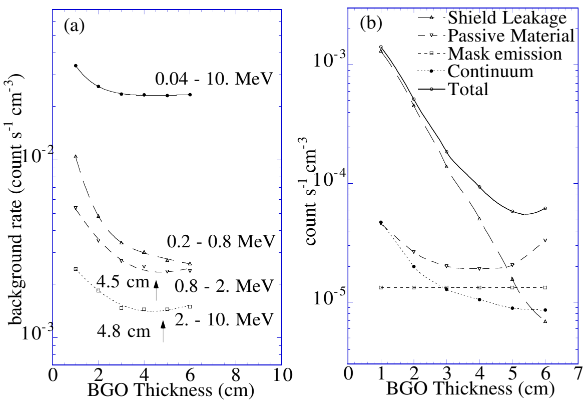

Figure 3: (a) Continuum background rate and (b) 511 keV line intensity as a function of the BGO shield thickness. The energy band for the continuum under the 511 keV line is 2.5 keV. Background and efficiency reductions due to PSD are included.

keV background rate is obtained for BGO thicknesses between 5 and 5.5 cm.

3.6. Optimized sensitivity

The 3σ narrow line sensitivity for an on-axis point source (Fig. 4) has been obtained with the reduced background (PSD, 511 keV signature, plastic scintillator under the coded mask). The total observing time and the lifetime fraction are 10^6 s and 0.95 respectively. This sensitivity estimate does not take into account other instrumental background lines (478 keV, 844 keV, 1809 keV). They are presently being studied in order to make the optimal choice of passive materials inside the shield.

Due to the large field-of-view of the spectrometer (25° FWHM) the effective observation time of any point in the inner Galaxy during the first two years of the mission will be 4 x 10^6 s, assuming that roughly 50% of the pointings are expected to be in or near (closer than 8°) the galactic plane.

4. CONCLUSION

We have described the calculations of the predicted performance for one particular model of SPI provided with a plastic scintillator. The internal β decays will be the major components of the background. However, the use of the event selections (PSD and "511 keV line signature") allows the partial rejection of the localized β^- and β^+ decay events, reducing the total background by a factor $\approx$2 at 1.5 MeV. Background calculations have been performed for several lateral and bottom shield thicknesses leading to an optimum shield thickness of 5.5 cm.

The sensitivity presented in Fig. 4 is applicable to on axis point sources and narrow γ-ray lines. It varies roughly with the square root of the energy width of the observed γ-ray line. Indeed, the broader the line,

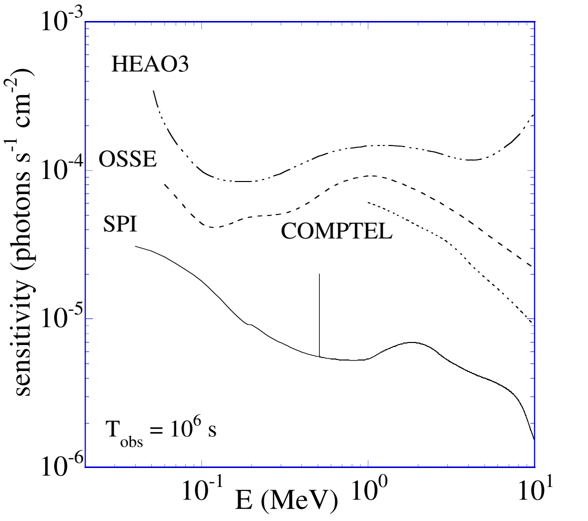

Figure 4: Estimated 3σ narrow line sensitivity for the spectrometer with event selection and a plastic scintillator set under the mask. Also plotted, the sensitivity of HEAO3, OSSE and COMPTEL for comparison.

the more background under the line is counted decreasing the signal to noise ratio. SPI sensitivity for some broad features of SNIa spectra are estimated in Isern et al. (1996). For imaging performances, please refer to Connell and Skinner elsewhere in this proceeding.

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