SPI: A High Resolution Imaging Spectrometer for INTEGRAL

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Abstract. SPI (Spectrometer for INTEGRAL) is a high spectral resolution gamma-ray telescope using cooled germanium detectors that will be flown on board the INTEGRAL mission in 2001. It consists of an array of 19 closely-packed germanium detectors surrounded by an active bismuth germanate (BGO) anti-coincidence shield. The instrument operates over the energy range 20 keV to 8 MeV with an energy resolution of 1-5 keV. A tungsten coded-aperture mask located 1.7 m from the detector array provides imaging over a 15° fully-coded field-of-view with an angular resolution of $\sim$3°. The point source narrow-line sensitivity is estimated to be 3-7 $\times$ 10^{-6} ph cm^{-2} s^{-1} over most of the range of the instrument (E $>$ 200 keV) for a 10^6 s observation. With its combination of high sensitivity, high spectral resolution and imaging, SPI will improve significantly over the performance of previous instruments such as HEAO-3, OSSE, and Comptel. It can be expected to take a major step forward in experimental studies in nuclear astrophysics. The SPI instrument is being developed under the auspices of the European Space Agency by a large international team of scientists and engineers in both Europe and the United States.

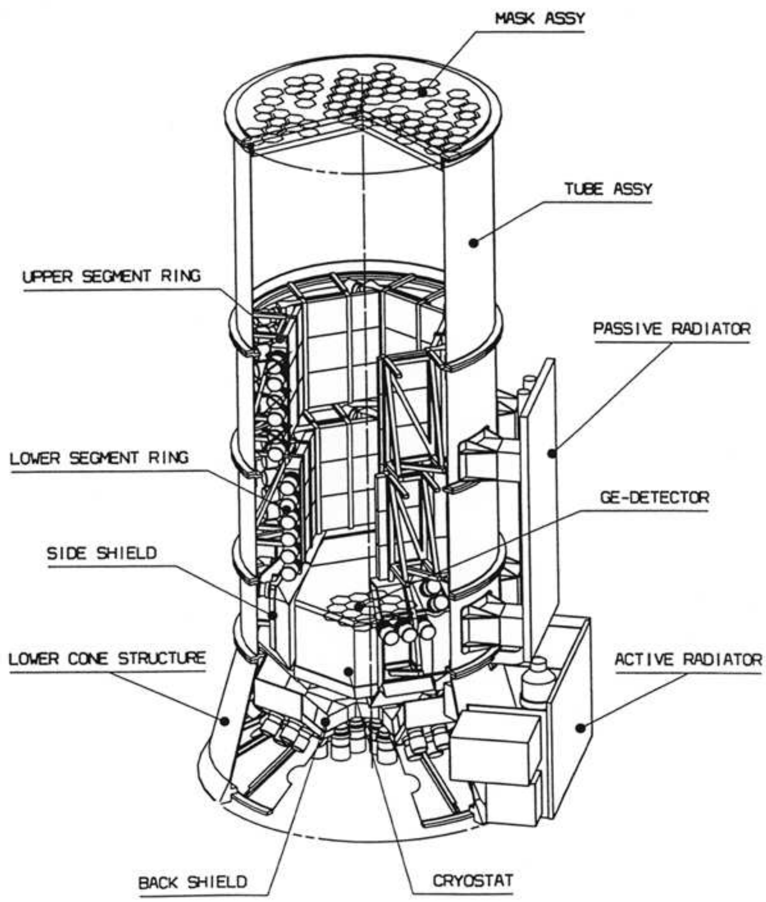

FIGURE 1. Spectrometer for INTEGRAL (SPI).

GENERAL DESCRIPTION

The Spectrometer for INTEGRAL (SPI) is a new telescope that incorporates the best current technology for fine spectroscopy in the gamma-ray region (for more detail see [1,2]). It is one of the two major instruments on the ESA INTEGRAL mission. INTEGRAL is the second of the ESA Medium-Class Missions (M2) and is scheduled for launch in the first half of 2001. It will be the successor to the NASA Compton Gamma-Ray Observatory (CGRO) and will make a significant step forward in gamma-ray astronomy particularly in the areas of fine spectroscopy and fine imaging. SPI employs an array of 19 high-resolution cooled germanium detectors in a close-packed hexagonal array (see Fig. 1). The energy range is 20 - 8000 keV, and over this range the energy resolution varies from $\sim$ 1 to 5 keV FWHM. The detectors are cryogenically cooled by two dual Stirling cycle refrigerators to a nominal operating temperature of 85K. In addition to providing a precise determination of the photon energy the Ge detector array also acts as an imaging device. The positional information comes from the knowledge of which detector was impacted, so the camera has only 19 pixels. Nevertheless, it can provide valuable information on the spatial distribution of the gamma-ray emission. A tungsten coded-aperature mask is located 1.7 m from the detector plane. Images are formed by deconvolving the shadow pattern cast by this mask on the detector plane. The fully-coded field-of-view of the telescope is 15° and the angular resolution is $\sim$3° FWHM. Extensive simulations of the imaging performance have been carried out at the U. of Birmingham.

The Ge detector array is surrounded by an active anti-coincidence shield made of bismuth germanate (BGO) scintillator (see Fig. 1). This hi-Z material is ideally suited to suppressing the strong flux of background radiation generated in both the SPI instrument and in the spacecraft. For long observations SPI is background-limited, and it is critical to maintain the overall instrument background at the lowest possible level. Further suppression of the internal Ge detector background is obtained through the use of on-board pulse shape discrimination (PSD).

Extensive calculations and modelling of the SPI background have been performed [3–5]. Based on these simulations, the predicted narrow-line sensitivity for SPI is $\sim 2 \times 10^{-5}$ ph cm^{-2} s^{-1} at 511 keV (note that this value is high due to the present of an instrumental background line at 511 keV) and $\sim 5 \times 10^{-6}$ ph cm^{-2} s^{-1} at 1 MeV for a 10^6 sec observation. These sensitivities are typically a factor of 10 - 50 times better than the narrow-line sensitivities of prior instruments.

SPI is co-aligned on the INTEGRAL bus (a derivative of the XXM bus) with the other principal telescope, IBIS [6], and the two monitor instruments, JEM-X [7] and OMC [8]. More detail on these instruments and the overall mission can be obtained at http://www.rssd.esa.int/SA-general/Projects/Integral/integral.html. The baseline mission scenario for INTEGRAL is to be launched on a Proton vehicle into a 48-hr orbit with an apogee of 75000 km and a perigee of 46000 km. In this orbit there will be very little loss of data due to passage through the radiation belts or earth occulation. In contrast the typical CGRO observational duty cycle is 35%. The spacecraft is constrained to point within 90°$\pm$ 40° of the sun at the beginning of life and 90°$\pm$ 30° at the end of life. Nominal mission lifetime is 2 years with a likely extension to 5 years. Final assembly, integration and test of the SPI experiment will take place at CNES, Toulouse, France. The following sections discuss various SPI subsystems in more detail.

DETECTOR/CRYOSTAT SUBSYSTEM

Each Ge detector is encapsulated in its own hermetic enclosure to protect it from contamination and to ease integration and replacement, if necessary. The lightweight capsules are constructed from aluminum and are sealed by electron beam welding after installation of the Ge detector. The 19 detector capsules are contained within a cryostat which serves to thermally isolate them from the ambient environment so that they can be cooled to the required 85 K operating temperature. The detectors are mounted to a cold-plate that is connected via a cold-finger to the Stirling cycle coolers that are located outside the BGO shield. The cryostat itself is thermally isolated from the surrounding shield and is operated at a temperature of 210 K to decrease the thermal load on the cold plate and Ge detectors. An on-board annealing capability (up to 100 C) is included to remove radiation damage effects if necessary. The cold plate, cold-finger, and most of the cryostat are all constructed from beryllium. This is because beryllium produces much less background (particularly at 511 keV) than all other materials suitable for cryostat construction. Also it introduces only a small amount of absorption at the 20 keV instrument threshold. A preamp for each Ge detector is mounted to the cryostat immediately behind the detector array cold plate. The detector/cryostat assembly will be fabricated and integrated at CESR and CNES, Toulouse, France.

BGO ANTICOINCIDENCE SHIELD

The detector/cryostat array is surrounded by an active BGO anticoincidence shield. The shield serves both to suppress instrument background (due to both internal and external sources) and to limit the SPI field-of-view. The mean pathlength in BGO traversed by a photon that impacts the detector array is $\sim$5 cm. It was found through extensive modelling [4,5] that a minimum in the overall 511 keV background was obtained for a shield thickness of $\sim$ 5 cm. This is as a result of the competition between externally-produced background which goes inversely with shield thickness and background due to neutron production in the shield itself which is roughly proportional to shield thickness. The shield is constructed of 90 different BGO modules. Each module is viewed by two redundant PMTs. Shield dead-time is a prime consideration. Extensive simulations and laboratory measurements have been made and the design of the electronics has been optimized to minimize this dead time. The internal housing of the shield is constructed from a low-Z light-weight carbon composite to minimize the amount of background producing inert material inside the shield. The shield subsystem will be fabricated, integrated and tested at MPE/Garching in collaboration with DASA.

CODED APERTURE MASK

The coded aperture mask is constructed from 3-cm thick hexagonal tungsten blocks mounted on a graphite-epoxy honeycomb plate that has a high transparency to gamma-rays. The tungsten blocks are >90% opaque over the entire SPI energy range. The mask pattern has been optimized for the SPI geometry and has 120° rotational symmetry. The mask elements are the same size as the detector modules (6 cm). With a mask/detector separation of 1.7 m the angular resolution of SPI will be $\sim 3°$ FWHM. The mask subsystem is the responsibility of the University of Valencia, Spain.

ELECTRONICS

Each detector has its own associated electronics that includes preamp, shaping amp, discriminators and ADC. The detector signals are digitized to 15 bit accuracy and time-tagged to an accuracy of ~ 100 μsec. In the normal mode the pulse height, time tag and PSD information for every accepted event (i.e. those the do not trigger the anticoincidence shield) are transmitted to the ground. Multiple-detector events are also recorded and transmitted. These constitute as much as 30% of the total event rate at higher energies. In addition the bad events (those that trigger the anticoincidence shield) are accumulated into 19 spectra (1 for each detector). These spectra are periodically (~30 min) transmitted to the ground and will provide useful information to better define the in-flight calibration. In addition to the pulse-height and time tag information, various housekeeping parameters (count rates, temperatures, voltages, mode flags) are included in the telemetry stream. The analog front-end electronics is being developed at CESR/Toulouse, the digital front-end electronics at CEN/Saclay and the digital processing electronics at CNES/Toulouse.

Additional electronics (PSD) is included to aid in suppresssion of internally-produced detector background. In the energy range 0.2-1.5 MeV the dominant component of the background results from β-decays in the Ge detectors induced primarily by secondary neutrons. These β-decays go primarily into the ground state (i. e. no accompanying photon). Since the range of the β in Ge is short (<few mm) the energy deposition of these events is localized to a small region. This is in contrast to the primary photons that constitute the signal. Most of these photons undergo multiple compton scattering before either loosing all of their energy or departing the detector. The current pulse generated by an interaction in the Ge detector depends on the location and multiplicity of the interactions in that detector. By analyzing this pulse (with the PSD) one can distinguish between single- and multiple-site events. It is estimated that the background in the range 0.2-1.5 MeV can be reduced by as much as a factor of 10. The PSD electronics is being developed jointly by the Univ. of Calif., San Diego, the Univ. of Calif., Berkeley, and the Lawrence

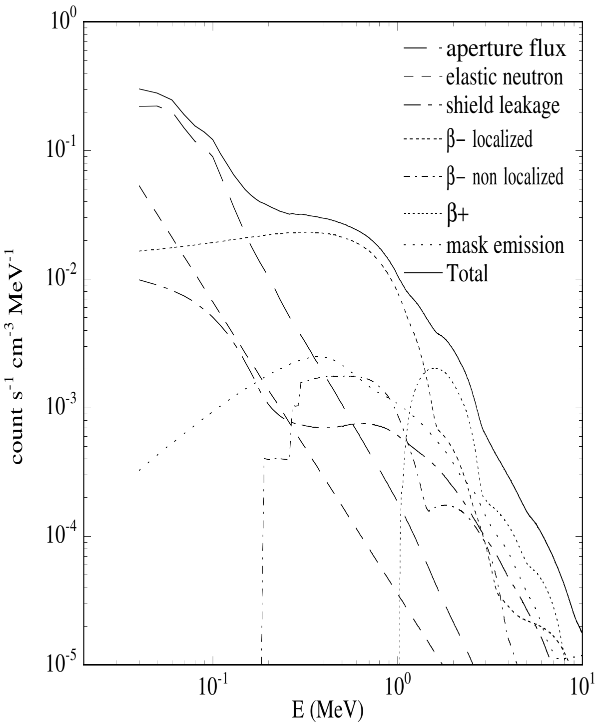

FIGURE 2. SPI instrumental background components.

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BACKGROUND AND SENSITIVITY

Extensive simulations of the SPI background have been performed using primarily the GEANT code developed for analyzing particle interactions in high-energy physics experiments. The results of these simulations have been used in many important instrument design trade studies (e. g. shield thickness, active vs. passive mask, cryostat materials, PSD performance). Every attempt has been made to optimize the SPI design to obtain the lowest possible background and highest possible sensitivity. The various components of the SPI background are shown in Fig. 2 [4,5]. Below 100 keV the aperture flux from the diffuse cosmic x-ray background dominates. From $\sim$ 200 keV to $\sim$ 1.5 MeV the dominant component is β^{-}-decay. It is this component that will be suppressed by the PSD. Above 1.5 MeV the strongest contribution is β^{+}-decay, but with significant contributions also from the tungsten mask and from shield leakage. In Fig. 3a [4,5] the SPI efficiency vs. energy is shown with and without event selection. The most important event selection is that due to PSD which causes a loss of efficiency due to its requirement

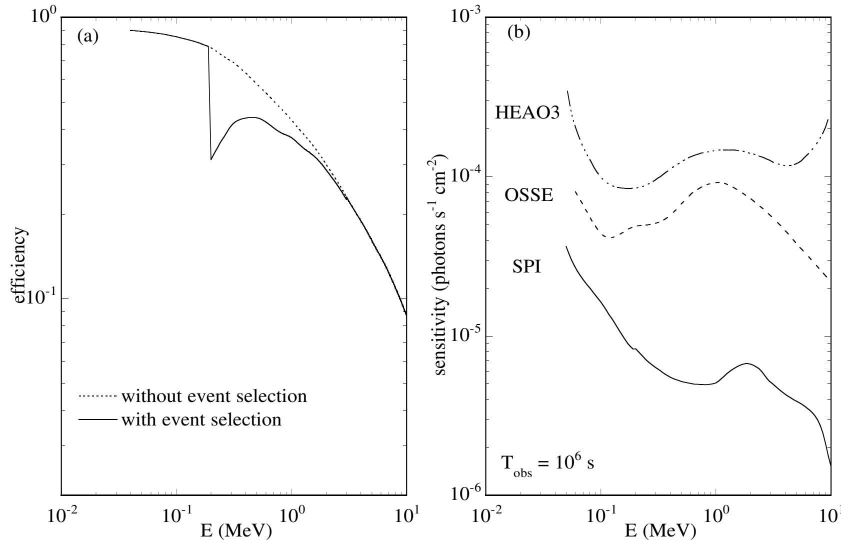

FIGURE 3. a) Efficiency vs. energy with and without event selection. b)SPI narrow-line sensitivity compared with other instruments.

for single-site interactions. In Fig. 3b [4,5], the SPI narrow-line sensitivity is shown as derived from the background given in Fig. 2 and the efficiency given in Fig. 3a. SPI is also compared with OSSE and HEAO-3 (the only previous comparable high resolution spectrometer). Typically SPI will be 20-30 times more sensitive to narrow lines than HEAO-3, and it will open an entirely new region of observational phase space in gamma-ray astronomy.

IMAGING

In the energy range of SPI the signal-to-background ratio will in general be small (typically a few to 10%). Knowledge of the background is critical to producing high quality gamma-ray images and spectra. This knowledge will be obtained primarily by using a dithering technique where the spacecraft pointing direction will varied in a pre-determined fashion. The typical pattern will be a 5 x 5 grid of pointings about the target direction each separated by 2°. Extensive imaging simulations have been performed for SPI. Most recently these simulations have used the GSFC-developed MGEANT code (http://lheawww.gsfc.nasa.gov/docs/gamcosray/legr/integral) to calculate individual photon interactions in the instrument and to produce event lists containing the energy losses in each of the SPI detectors. This has been done for a variety of different types of astrophysical gamma-ray sources (e.g. point sources of various spectra and positions, diffuse 511 keV, diffuse 1809 keV). These event lists were then fed into

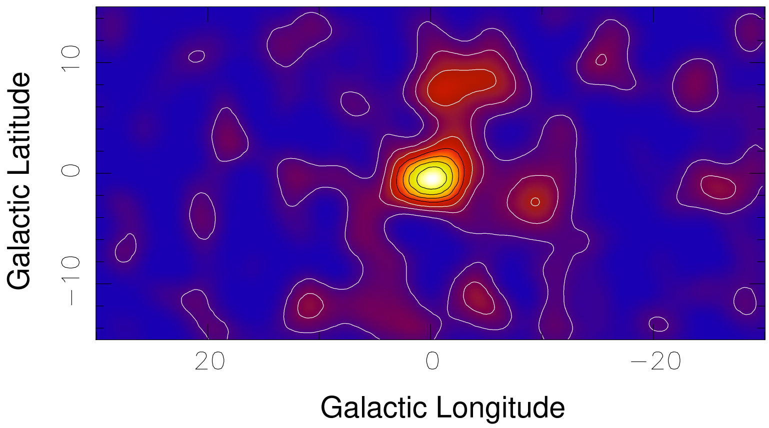

FIGURE 4. Simulated SPI map of OSSE 511 keV measured emission.

the Univ. of Birmingham-developed CAPTIF image processing package (http://www.sr.bham.ac.uk/~phc/CAPTIF) and simulated sky maps were generated. An example of such a map of the diffuse 511 keV emission is given in Fig. 4. The input data used was the measured OSSE 511 keV distribution [9,10]. The simulation reproduces quite well the essential features of the OSSE map. For more details on these simulations and other results see Connell et al [11].

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