THE SPI SPECTROMETER FOR THE INTEGRAL MISSION

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ABSTRACT. SPI (Spectrometer for INTEGRAL) is a high spectral resolution gamma-ray telescope to be flown on board the ESA mission INTEGRAL. It consists of an array of 19 closely packed Germanium detectors surrounded by an active anticoincidence shield of BGO. The imaging capabilities of the instrument are obtained with a tungsten coded aperture mask located 1.7 m from the Ge array. The fully coded field-of-view is 16° and the angular resolution ≈ 2°. The energy range extends from 20 keV to 8 MeV with a typical energy resolution ≈ 2 keV at 1 MeV. The point-source narrow-line sensitivity is estimated to be (3 - 7) x 10^{-6} ph/cm^{-2} s^{-1} over most of the energy range of the instrument (E > 200 keV) for a 10^6 s observing time. With these expected performances a major step forward can be expected in fine gamma-ray spectroscopy of astrophysical objects.

1. Introduction

The Spectrometer SPI for INTEGRAL is a new telescope which combines imaging and fine gamma-ray spectroscopy capabilities in the 20 - 8000 keV energy range. It is one of the two main instruments embarked aboard the INTEGRAL satellite; this mission being the second of the ESA Medium Class Missions (M2). INTEGRAL is planned to be launched in April 2001 on a Proton rocket into a 48 h orbit with an apogee of 75 000 km and a perigee of 45 000 km. The spacecraft is constrained to point within 90° ± 40° of the Sun. The nominal lifetime of the mission is 2 years with an expected extension to 5 years.

After the impressive results obtained in nuclear gamma-ray astrophysics by Comptel on the NASA Compton Gamma-Ray Observatory (CGRO), SPI will be able thanks to its high spectral resolution capabilities to contribute to a significant breakthrough, particularly in the nuclear astrophysics domain. For that a significant increase in the point source narrow line sensitivity is expected, i.e. few 10^{-6} ph/cm^2.s over most of the energy range of the instrument and for a 10^6 sec observation. This estimation is based on extensive calculations and modelling of the SPI background [1 and 2]. This sensitivity is a factor of ≈ 20 to 50 better than what was obtained by HEAO3, the last fine spectroscopy instrument in gamma-ray astronomy.

The main parts of the instrument (Fig. 1) are: a Ge-detector array to detect gamma rays, an anticoincidence BGO shield, and a mask which allows the imaging of point sources as in the SIGMA mission on GRANAT [3].

The following sections give a brief description of the main parts of the instrument. We will also indicate the share of responsibilities between the different institutes; the project team at CNES having the full technical responsibility of the instrument with final assembly, integration and tests.

The last section concerns the background evaluation and the expected sensitivity with some illustrations of the instrument response to astrophysical targets. For a complete analysis of the scientific objectives which can be achieved with such an instrument one can refer to the paper presented at the 2nd INTEGRAL Workshop held in St Malo on September 1996 [4].

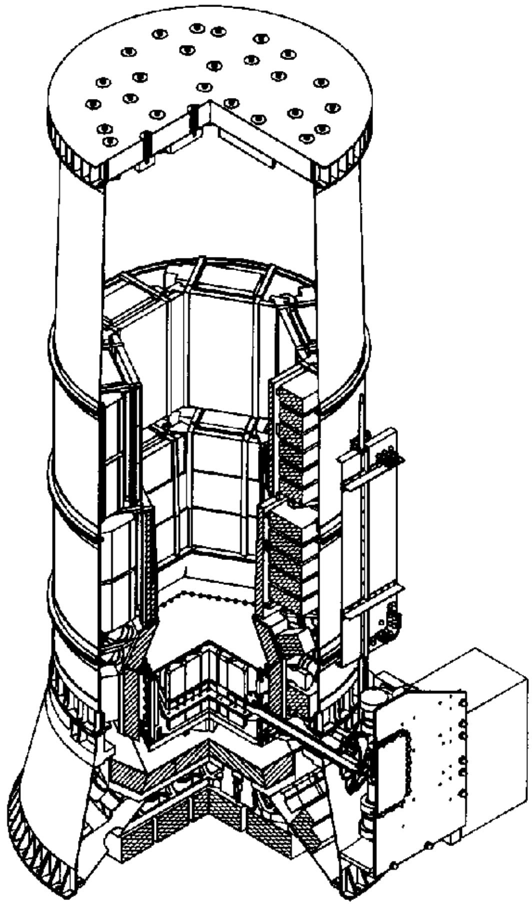


Fig. 1. The spectrometer SPI

2. The Ge detector array and its electronics

The Ge-detector array consists of 19 reverse electrode n-type Ge detectors. The detectors have a hexagonal shape with a side length of 3.2 cm and a height of 7 cm. The central bore is 6 mm in diameter and 6 cm in length. The center-to-center distance between the detectors is 6 cm. Each crystal is individually mounted inside a partially pressurized Al capsule. The closely packed array of Ge detectors is fixed on a Be plate. The detector plane is placed inside a Be cryostat so that it can be cooled to the required 85 K operating temperature. The connection of the detector plane to the Stirling cycle coolers located outside the anticoincidence BGO shield is realized via a Be cold finger (Fig. 2). To minimize the power to be extracted by the cryocoolers, the cryostat itself is thermally insulated and operated at a temperature of 210 K. This is achieved by a passive radiator with ammonia-driven heat pipes connected to the insulated cryostat. To recover their performances following the radiation damages expected after about one year in orbit, the detectors can be regenerated in-flight by annealings up to 100°C.

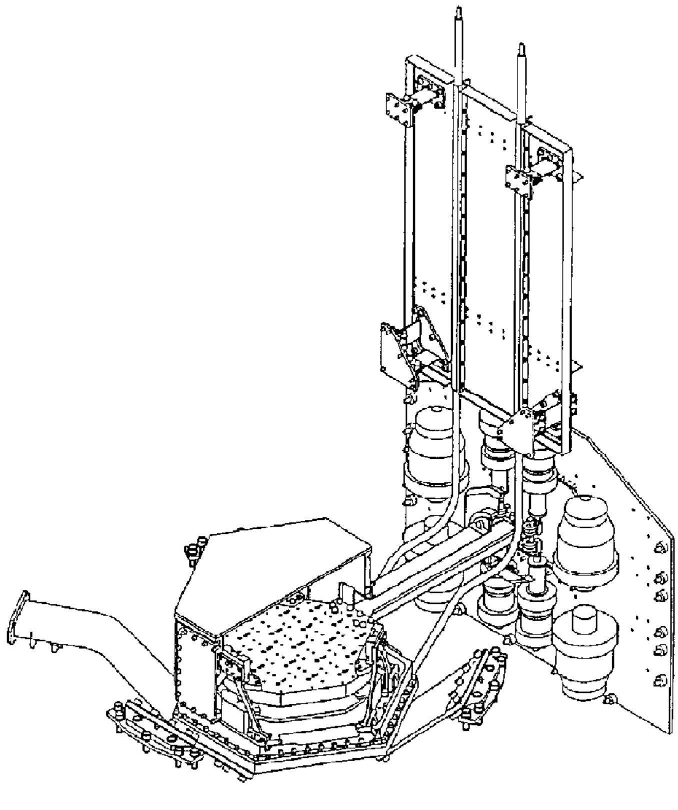


Fig. 2. General design of the cryostat

Each detector has its own associated electronics that includes preamplifiers, shaping amplifiers, discriminators and Analog to Digital Converters (ADC). The detector signals are digitized with a 15 bit ADC resolution and time-tagged with an accuracy of ≈ 100μsec. In the normal mode the pulse height, time tag and Pulse Shape Discrimination (PSD) information for every good photon (i.e. those that do not trigger the anticoincidence shield) is 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 detector array with the Analog Front-End Electronics (AFEE) are being developed at CESR Toulouse and the Digital Front End Electronics (DFEE) at CEN Saclay. The Ge crystals are produced by Hoboken under the responsibility of P. Leleux from Louvain University (Belgium).

The cryostat is developed by CNES and the cryocoolers are under ESA responsibility.

The Pulse Shape Discrimination (PSD) device is designed to reduce the background in the 200 keV - 1.5 MeV energy range where β^- decays in the Ge detectors are the dominant component of the background. These β^- decays go mainly in the ground state (without accompanying photons); as the range of a β^- in the Ge is less than few mm this type of event can be considered as localized.

On the other hand, the gamma rays interact in this energy range mainly through multiple interactions ; Compton interaction being the first and dominant one. Therefore the energy deposit appears in two or more sites. These are non-localized events.

The aim of the PSD electronics is to separate with a good efficiency single and multiple events and to reject a large part of the background with a low degradation of the detection efficiency. The laboratory tests [5] demonstrate a significant increase of the sensitivity in the 200 keV - 1.5 MeV energy range ; around 800 keV it can reach a factor of ≈ 2 equivalent to an increase in the detector area by a factor of 4. The performances of the PSD electronics will be tested by the University of California Berkeley during a long-duration balloon flight around the South Pole. The PSD development is under the responsibility of the University of California at San Diego (UCSD) and the Space Sciences Laboratory (SSL) at Berkeley.

3. The BGO anticoincidence system (ACS)

To shield the Ge detectors against background radiations and to limit the SPI field-of-view, a BGO shield surrounds the Ge array. The BGO thickness has been optimized using Monte-Carlo simulations [6 and 7]. A thickness of ≈ 5 cm has been chosen for the rear and side shields. This is a compromise because an increase of BGO thickness leads to a reduction of gamma-ray transmission but also to an increase of secondary particles production, particularly neutrons which are an important source of background for the Germanium detectors.

In order to increase the shield efficiency it is planned to set the energy threshold at 50 keV. The electronics has been designed for that keeping in mind the objective to minimize the dead time due to the large counting rate expected (80 000 counts/s at solar maximum). A more detailed description of the ACS can be found in Lichti et al., 1996 [8]. The anticoincidence sub-system is developed at MPE Garching.

4. The coded aperture mask

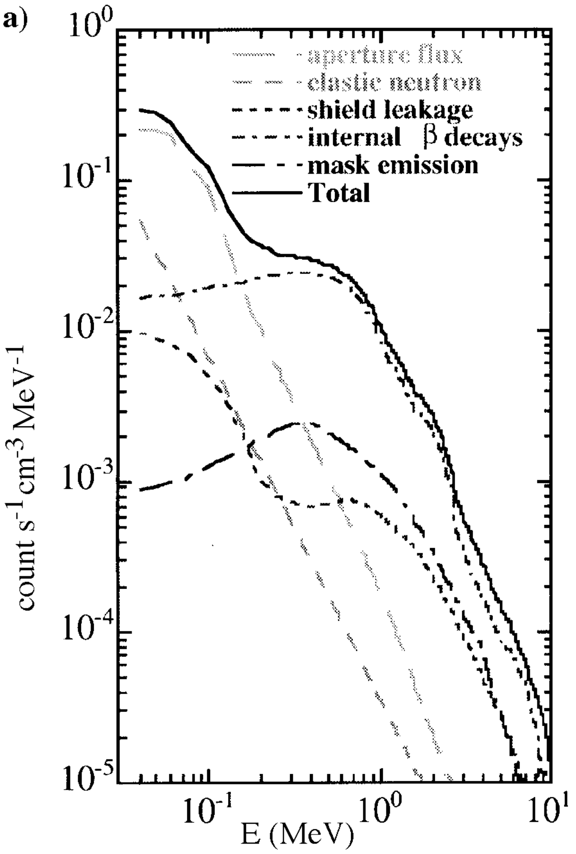
The mask is made of 3 cm thick hexagonal tungsten blocks mounted on a graphite-epoxy honeycomb plate with a high transparency to gamma rays (80 % at 20 keV and 90 % at 50 keV). The tungsten blocks are > 90 % opaque over the entire SPI energy range. The opaque mask elements (63) have the same size as the detector modules (6 cm). The distance mask-detector is 1.7 m. These values lead to an angular resolution for point sources of ≈ 2° - 3° FWHM, and for the long axis a fully coded field-of-view of 16°, with a zero sensitivity at ≈ 34°. The mask development is under the responsibility of the University of Valencia (Spain).

It is planned to add to this mask a very thin plastic scintillator which will be delivered by the IFCTR (Italy). Indeed, Monte Carlo simulations have shown that a significant background reduction can be achieved, especially at 511 keV [9], by placing this plastic scintillator as close as possible to the lower side of the passive mask.

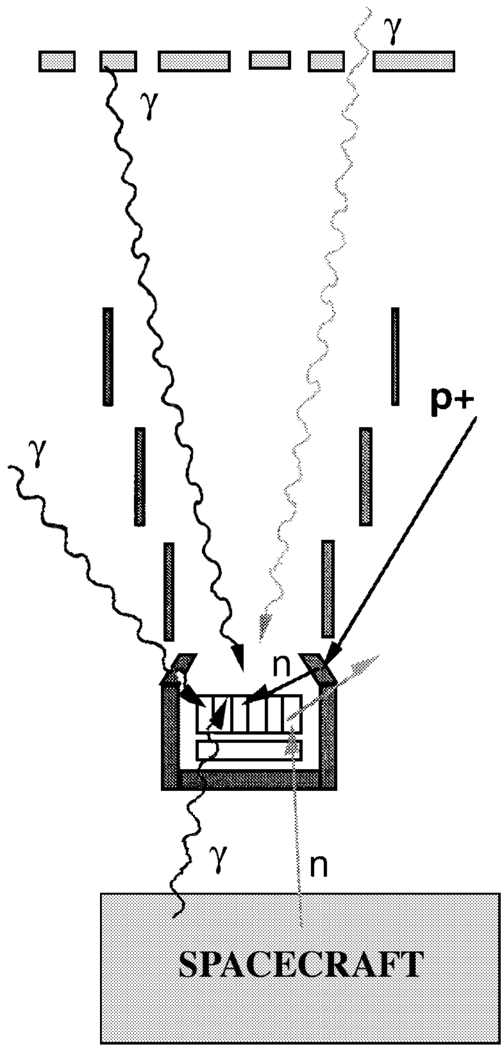
5. Background and sensitivity

Extensive simulations of the SPI background have been performed using the GEANT code developed for analysing particle interactions. The estimations have been performed at CESR-Toulouse by P. Jean and P. von Ballmoos, at CEN-Saclay by B. Cordier and N. Diallo, and at GSFC-Washington by J. Naya and B. Teegarden. The possibility to cross-check these calculations, but also to estimate the background from balloon experiments (Hexagone and Hiregs) and from TGRS on the Wind satellite, gives confidence in the results. Extensive analyses of the background have been published [9]. The different background components are detailed in Fig. 3a/b.

a)



b)



The total background is understood as the sum of several components

• Aperture flux: cosmic diffuse γ-ray emission
• Internal β decays: radioactive nuclei induced in Ge by primary and secondary p^+, n
- β^- localized e.g. $^{75}Ge(\beta^-)^{75}As(gs)$
- β^- non-localized e.g. $^{75}Ge(\beta^-)^{75}As^* \rightarrow {}^{75}As + \gamma$ (265 keV)
- β^+ e.g. $^{68}Ga(\beta^+)^{68}Zn \rightarrow$ Two 511 keV photons
• Shield leakage: γ go through the shield without depositing energy in it or are not rejected because of electronic leakage.
- cosmic diffuse γ-ray emission
- photons from the spacecraft
• Elastic neutron scattering: n from the spacecraft, and dead masses
• Mask emission: γ from the mask induced by cosmic-ray particles

Fig. 3a/b. The continuum background components.

Moreover, taking into account the possible background reductions due to the PSD technique, and using the capability with the Ge array to separate (between ≈ 1 to 3 MeV) the gamma rays and the β^+ events, the SPI sensitivity has been calculated for narrow lines and for the continuum (Fig. 4.1 et 4.2.).

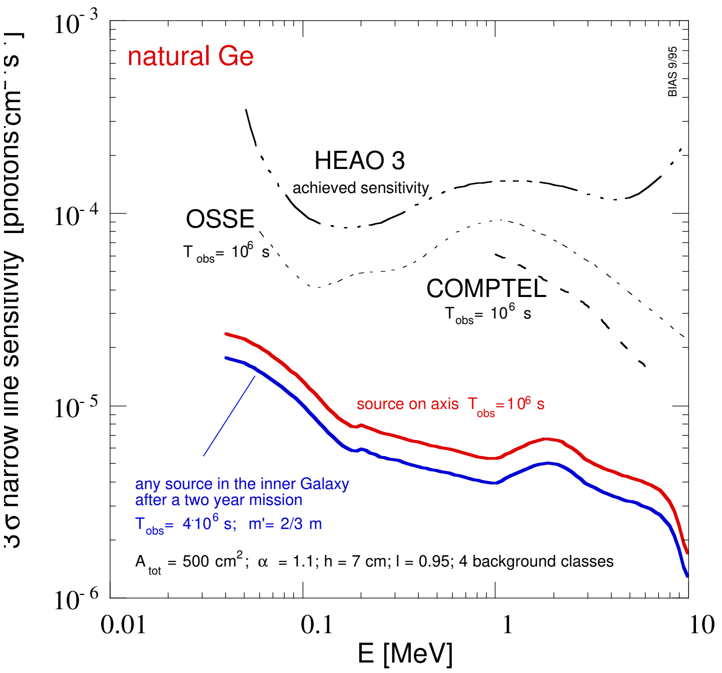


Fig. 4.1. Estimated 3σ narrow line sensitivity for the INTEGRAL Spectrometer (including a β^+ component)

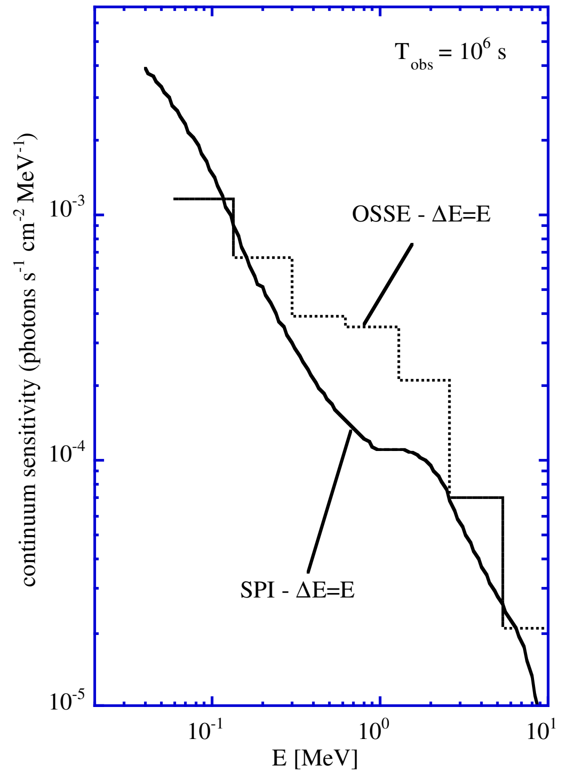


Fig. 4.2. Estimated 3σ continuum sensitivity for an on-axis point source

With the estimated background, simulated responses of the instrument have been obtained by G. Skinner and P. Connell from the Birmingham University [10]. Figure 5 gives an example of what can be expected for point sources situated in the galactic center region.

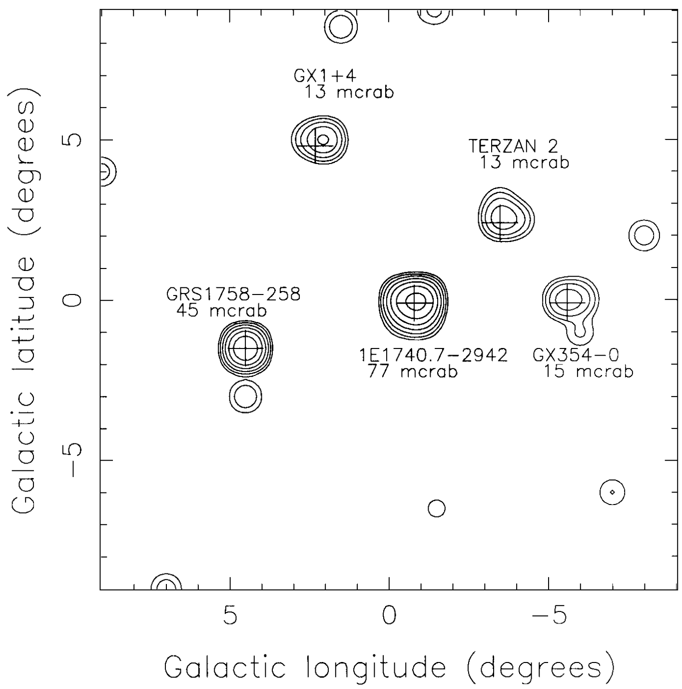


Fig. 5. Simulated observation of the galactic centre in the energy range 70-150 keV. Spacecraft pointing dithered over a 13x13 grid of 2 degree pitch. Total exposure 56 hours. Reconstruction using cubic B-spline technique. Source strengths based on Sigma data. Contours logarithmically spaced.

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