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 some examples of what might be the scientific impacts of the instrument are highlighted.

1. Introduction

SPI (Spectrometer for INTEGRAL) will be particularly devoted to nuclear gamma-ray astrophysics through the study of the gamma-ray lines from radioactive elements which are produced and emitted during nova or supernova explosions (Table 1) (Prantzos N., 1996). The long-lived radioelements can diffuse in the interstellar medium and populate extended regions. This is the case for ^{26}Al which has been traced by its characteristic gamma-ray line at 1.809 MeV. Some of these radioactive elements are also β^+ emitters and, due to their long lifetime (≈ 10^5 years), the positrons can occupy large regions in the interstellar medium. Their annihilations are revealed by an extended 551 keV emission already observed.

The NASA Compton Gamma-Ray Observatory (CGRO) has realized a remarkable breakthrough in this field, even if previous experiments on board satellites (HEAO-C and SMM) and balloons (Hexagone - Gris) had already opened the domain of nuclear gamma-ray astrophysics.

Before giving a brief description of the main characteristics of the SPI spectrometer aboard the ESA INTEGRAL satellite, we present an overview of the interest of nuclear gamma-ray lines as tracers of recent nucleosynthesis phenomena.

Nucleosynthesis theories have been extensively developed during the last decades but it is still very important to calibrate the models of Supernovae (SN) or nova explosions, checking among other things the yield of ejected elements. A direct access to the masses for some of them which are radioactive has already been achieved by Comptel and OSSE on CGRO. Depending on the type of supernovae or novae these lines allow to constrain the models of these explosive events and to better understand the processes which lead to the enrichment of the galactic interstellar medium in heavy elements. Therefore these studies on nuclear gamma-ray lines constitute a significant contribution for the understanding of the chemical evolution of the galaxy.

DECAY CHAIN	MEAN LIFE* (YR)	LINE ENERGIES (MEV)	SITE	PROCESS
^{56}Ni → ^{56}Co → ^{56}Fe	0.31	<u>0.847</u> (1.) <u>1.238</u> (0.685) 2.598 (0.17) 1.771 (0.45)	SN [SN 1987A, SN 1991T]	NSE
^{57}Co → ^{57}Fe	1.1	<u>0.122</u> (0.86) <u>0.136</u> (0.11)	SN [SN 1987A]	α-NSE
^{22}NA → ^{22}Ne	3.8	1.275 (1.)	Novae	*Ex.*H
^{44}Ti → ^{44}Sc → ^{44}Ca	70-96	<u>1.156</u> (1.) 0.068 (1.) 0.078 (0.98)	SN [Cas A]	α-NSE
^{26}Al → ^{26}Mg	1.1 10^6	<u>1.809</u> (1.)	WR, AGB (Novae) SNII [Galaxy, Vela]	*St.*H (*Ex.*H) *St.*+*Ex.*Ne, *St.*H, ν
^{60}Fe → ^{60}Co → ^{60}Ni	2.2 10^6	1.322 (1.) 1.173 (1.)	SN	n-NSE

* For double decay chains the longest lifetime is given.
Underlined: lines already detected; Numbers in *parentheses*: branching ratios; In *brackets*: sites of lines detected; *St.*: Hydrostatic burning; *Ex.*: Explosive burning; NSE: Nuclear statistical equilibrium; α: α-rich "freeze-out"; n-: normal "freeze-out"; ν: neutrino-induced nucleosynthesis.

Table 1. Cosmic radioactivities and γ-ray lines (Prantzos N., 1996)

2. Some scientific fields of interest for SPI

Compared to Comptel and OSSE on CGRO, SPI will have a much better energy resolution (E/ΔE = 500) and a better sensitivity. Therefore we can expect to have a more accurate understanding of the origin of the ^{26}Al and annihilation line distributions.

In the case of the ^{26}Al galactic distribution, the detection of the ^{60}Fe gamma-ray lines at 1.173 MeV and 1.322 MeV would be very helpful to clarify what is (are) the source(s) of this radioactive element. For instance if its origin is type II supernovae, as ^{26}Al and ^{60}Fe are co-produced in the same regions they will have the same spatial distribution. The profile of the ^{26}Al line is also very essential to know, especially after the observations obtained with the GRIS balloon experiment which reported a line profile surprisingly broad (ΔE = 5.4 ± 1.4 keV) (Naya J.E. et al., 1996) after removing the instrumental line width. So far such a broadening is not explained but different ways are opened (Chen W. et al., 1997). With a better sensitivity and good imaging capabilities SPI will be able to measure the broadening of the line for different regions, GRIS having a quite broad field-of-view of 100°. In addition, we can expect to separate foreground sources and to locate them in the galactic disk through the measurement of the centroïd of the line at the level of few 0.1 keV which can be achieved depending on the flux in the line and gives access to Δv measurements of some tens of kilometers. Such a discrimination of foreground sources might have a significant impact on the total ^{26}Al mass which has to be produced in our galaxy to explain the ^{26}Al diffuse emission.

Concerning the annihilation line mapped by OSSE, which is not an imager and has no fine spectroscopy capabilities, we can expect by the study of the line profiles in different emitting regions of the central galactic radian to better determine the physical conditions of the medium where the annihilations are produced. Indeed depending on the presence of different phases (cold or warm gas, ionized or not, dust…), the broadening of the annihilation line is different. Therefore the spectral resolution and the sensitivity of SPI can help to understand what are the galactic sources of the positrons.

Another interesting open area is connected with the detection by Comptel of the ^{44}Ti gamma-ray line at 1.157 MeV from the supernova remnant Cas A. This element is a source of the galactic ^{44}Ca, but is it only produced by type II Supernovae through ^{44}Ti ejecta ? The supernova rate seems too small to explain its abundance. Therefore what are the other sources of ^{44}Ca?. In any case the production of this radioactive element is important by itself because for core collapse supernovae as it is produced in deep regions near the mass cut of the supernova which defines the mass which falls back onto the remnant its production is quite sensitive to the SN explosion details with a strong impact on the models. ^{44}Ti is also important because through its β^+ decay (see table 1) it can contribute significantly to the existence of positron extended regions. Indeed this element has a half life long enough to escape from the supernova envelop after a type II explosion, whereas it is certainly not the case for the e^+ produced through the ^{56}Co decay chain even if these nuclei are more abundant. To approach the rate of SN in our Galaxy it is important to look for the most recent SN remnants. From 6 to 24 galactic SN are expected during the last 300 years (Van den Bergh S. and Tammann G.A., 1991), but only 2 or 3 nearby galactic supernovae have been identified. ^{44}Ti can be used to detect a significant fraction of these supernovae which are optically obscured. For instance a supernova 100 years old at 10 kpc might give a flux of few 10^{-5} ph/cm^{2}s at 1.156 MeV which is quite detectable by SPI.

Concerning SN real time observations, estimates have been done concerning the possible detection of type I Supernovae by SPI, depending on the models: deflagration or detonation. For instance with a production of 0.7 Solar Mass of ^{56}Ni, a type I SN explosion in Virgo Cluster would give at 847 keV a flux of 7 10^{-6} ph/cm^2 s. Its detection by SPI is possible and the study of the line profile would be of prime importance for the understanding of the dynamic of ejecta through the velocity measurements which can be approached by the gamma line profiles. This has been clearly shown by the high spectral resolution observations of ^{56}Co lines after the explosion of SN1987A (Tueller J. et al., 1990).

Another field which remains to be explored concerns gamma-ray lines produced by novae even if they have not yet been detected ; indeed only upper limits have been reported by Comptel (Iyudin A.F. et al., 1997). The possibility to observe ^{22}Na gamma-ray line at 1.275 MeV and even ^{7}Be at 478 keV and 511 keV annihilation lines (Hernanz M. et al., 1996) is essential to constrain the present nova models. Today large uncertainties exist in the expected flux from these radioelements, depending particularly on the chemical composition at the onset of the explosion and on the efficiency of the element mixing by convection.

Another very exciting domain opened by Comptel is the production of lines by the interaction of cosmic rays with the dense clouds in the interstellar medium. The detection of Carbon and Oxygen broad gamma-ray lines around 4.4 and 6.1 MeV observed from the Orion nebulae has opened exciting discussions around the energetic particles and their composition in these regions. If the lines have a typical MeV broadening, it is difficult to expect with SPI more than what has been already obtained by Comptel, except if these broad lines are the superposition of narrow line contributions as it has been suggested (Bykov A.M. et al., 1996). In any case this point has to be checked for Orion and other nearby clouds. In addition it has been shown that the presence of OB associations inside a superbulle and near molecular clouds such as in Orion might lead to Carbon and Oxygen gamma-ray lines which might be observable with SPI (Parisot E. et al., 1997).

Finally, with a much better energy resolution and sensitivity than the previous instruments, SPI will study X and gamma-ray sources to determine their continuum emission and look for lines which can add to the continuum spectrum for instance annihilation lines possibly due to the interaction of electrons jets with the dense clouds which might exist in their vicinity. One interesting candidate is the 1E1740.7-2942 micro quasar source (Bouchet L. et al., 1991 and Mirabel I.F. et al., 1992). Another example is the transient line at 480 keV discovered by SIGMA in Nova Muscae and which can be explained by a redshifted annihilation line produced in the vicinity of the black hole. Cyclotron absorption features are also of great importance due to their signature of strong magnetic fields around neutron stars in X-ray binary systems.

These are examples of burning questions on which the SPI spectrometer can give an interesting contribution. A more detailed analysis of the scientific objectives has been given in the response to the Announcement of Opportunity issued by ESA in 1994 (ref. SCI(94)1) and in two recent presentations of the instrument (Mandrou P. et al., 1997 and Lichti G. et al., 1996). These have to be put in perspectives especially with the numerous results obtained by Comptel and presented in a paper by Schönfelder in 1996.

3. The instrument

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. INTEGRAL, the second of the ESA Medium Class Missions (M2), is planned to be launched in April 2001 on a Proton rocket into a 48 h orbit. The nominal lifetime of this observatory is 2 years with a possible extension to 5 years.

The main parts of the instrument (Figure 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 (Roques J.P. et al., 1990).

3.1. 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 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 an operating temperature around 85 K. The connection of the detector plane to the Stirling cycle coolers located outside the anticoincidence BGO shield is realized via a Be cold finger (Figure 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, the detectors can be regenerated in-flight by annealings up to 100°C.

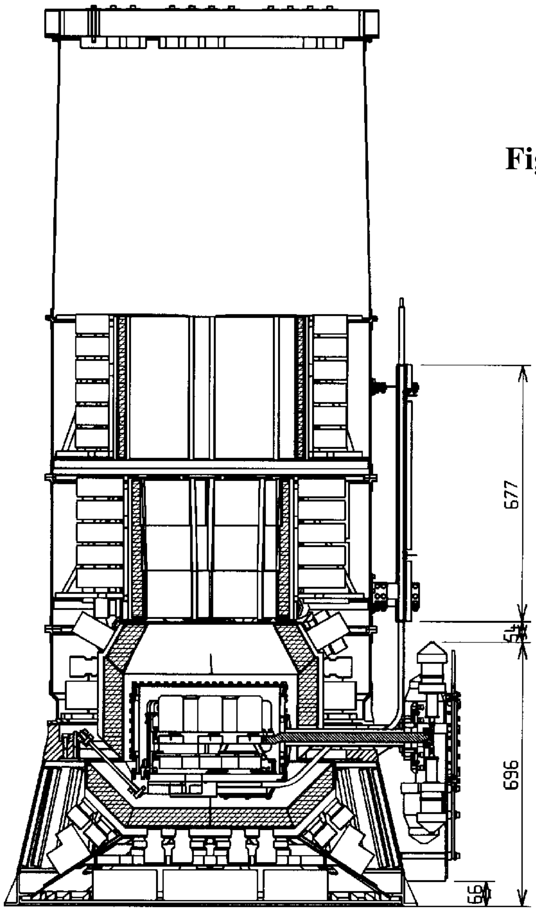

Fig. 1. SPI : Spectrometer for INTEGRAL

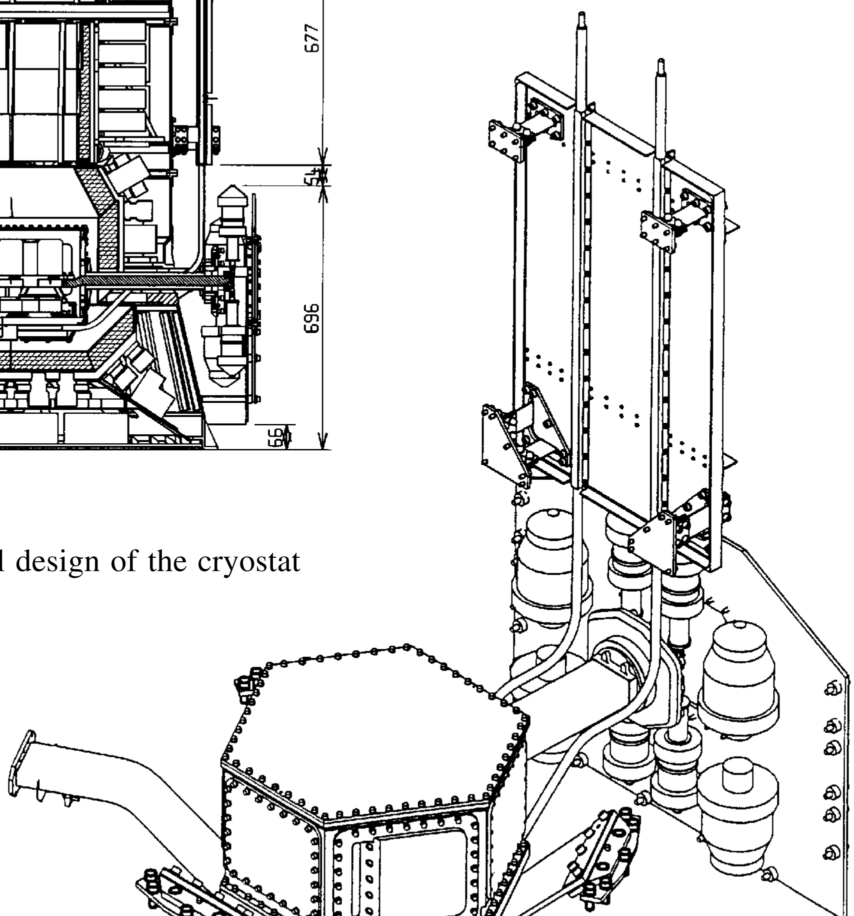

Fig. 2. General design of the cryostat

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.

A 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 (see § 4). 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 events are non-localized.

The aim of the PSD electronics is to separate with a good efficiency these two types of events and to reject a large part of the background with a limited decrease in the detection efficiency. The laboratory tests (Slassi-Sennou S. et al., 1996) 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. 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.

3.2. 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 (Georgii R. et al., 1996 and Jean P. et al., 1996). 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. A more detailed description of the ACS can be found in Lichti et al., 1996. The anticoincidence sub-system is developed at MPE Garching.

3.3. 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 (Jean P. et al., 1997), by placing this plastic scintillator as close as possible to the lower side of the passive mask.

3.4. Background and sensitivity

Extensive simulations of the SPI background have been performed using the GEANT code developed for analyzing particle interactions. A complete analysis of the background has been published (Jean P. et al., 1997). This study allowed to identify the different background components which are detailed in Figure 3. At low energy (< 200 keV) due to the large field-of-view of the instrument the main component of the background is the cosmic diffuse X-ray emission in the field-of-view. Above 200 keV to few MeV the background is dominated by the internal β decays induced in the Ge crystals by primary and secondary protons, and by secondary neutrons mainly produced in the anticoincidence material (≈ 400 kg of BGO). Above few MeV the leakage of the shield for the cosmic diffuse gamma rays and the gamma rays produced in the spacecraft starts to be the dominant contribution. But the mask emission, calculated here without the presence of a plastic scintillator just below the mask, is comparable to the shield leakage. Another contribution which has been estimated is due to elastic neutron scatterings. In the SPI energy range this contribution is always quite small (figure 3).

The comparison between the calculations and the observations has been done for balloon experiments (HIREGS, GRIS, HEXAGONE) and for the satellite experiment TGRS on board the WIND satellite. The results are in good agreement giving confidence in the calculations done for SPI.

Taking into account this background estimation, some ways to reduce it have been explored. First the PSD can be used between 200 keV and few MeV to separate β^- decays which are largely localized events from gamma rays which interact through multiple interactions, for instance Compton followed by photoelectric interactions : these are non-localized events. Very soon the efficiency of the PSD will be determined precisely with a repre-sentative detector and its flight electronics.

A second way to reduce the background in the MeV range (from 1 to 3 MeV) is to use the advantage of the array of detectors. When a β^+ deposits its energy in one Ge crystal, two photons at 511 keV are produced and there is a high probability for having either one of them that goes in the anticoincidence BGO crystals or one of the 511 keV photons which interacts in one of the next detectors giving a 511 keV signature. In both cases the corresponding β^+ can be eliminated.

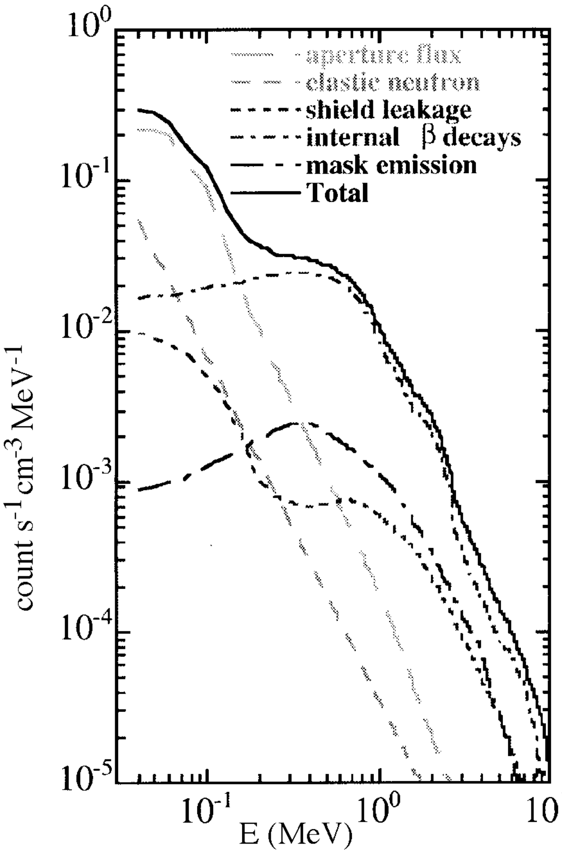

Fig. 3. The continuum background components

Above around 3 MeV the dominant interaction of the photons being by pair production, we cannot separate β^+ and photon interactions ; fortunately the β^+ contribution falls dramatically above this energy. In this energy range we plan to reduce the background due to the passive mask by the addition of a plastic scintillator just below the mask. Moreover with such a plastic the background at 511 keV can be also significantly decreased from 4.7 10^{-4} counts s^{-1} cm^{-3} to 2.7 10^{-4} counts s^{-1} cm^{-3}. The interest of this plastic is illustrated in figure 4 showing clearly the importance of the mask emission when the distance mask - last BGO ring increases.

Finally the presence of the Ge-crystals array and a large fraction of multiple events above 1 MeV can be used to discriminate the photons inside and outside the field-of-view. In the case of a double interaction the respective energy deposits in two Ge crystals are different if the photon incidence is near the normal (in the field-of-view) or at a large zenith angle. Calculations are on-going to evaluate the possible background reduction which will be added to the previous one.

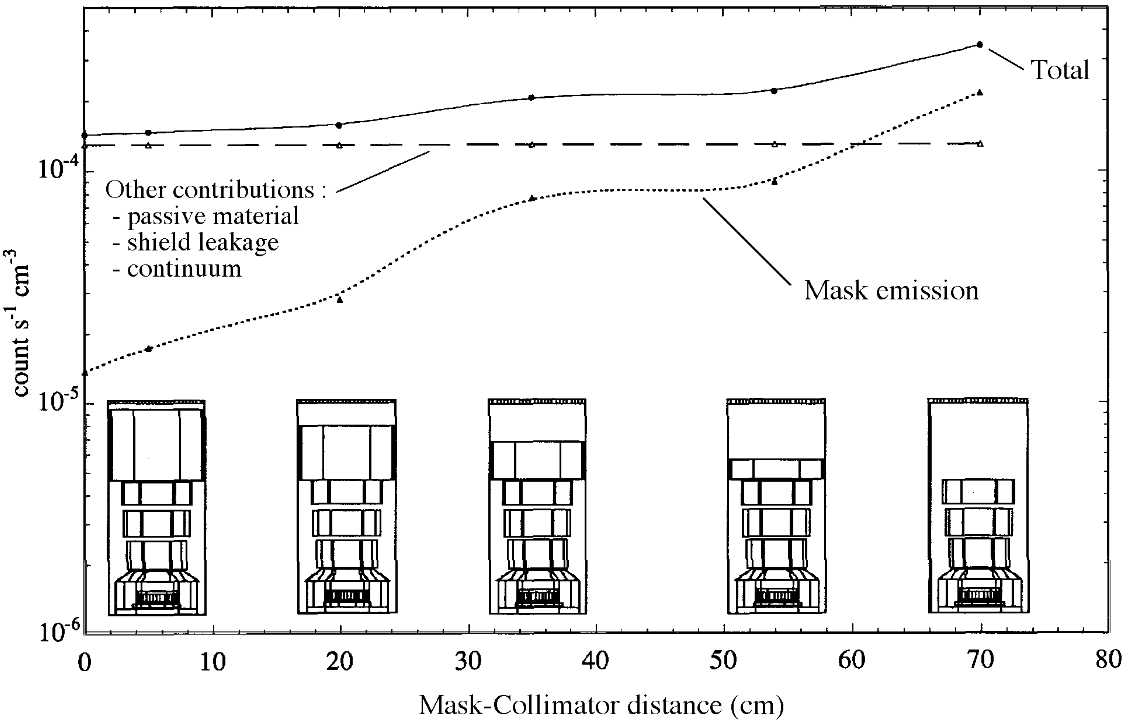

Fig. 4. 511 keV background contribution versus the distance between the mask and the last ring of the anticoincidence BGO shield.

The background estimate in Figure 3 completed by PSD rejection and β^+ discrimination has allowed the determination of the sensitivity to narrow lines (figure 5). If the line is broadened the sensitivity goes as the square root of the broadening of the line. At 1 MeV for instance, going from 2 keV to 18 keV means a decrease of the sensitivity by a factor 3.

Concerning the sensitivity for the annihilation line the expected value using a plastic scintillator below the mask is around 2 10^{-5} ph/cm^2 s. for a narrow line and for a typical observing time of 10^6 sec.

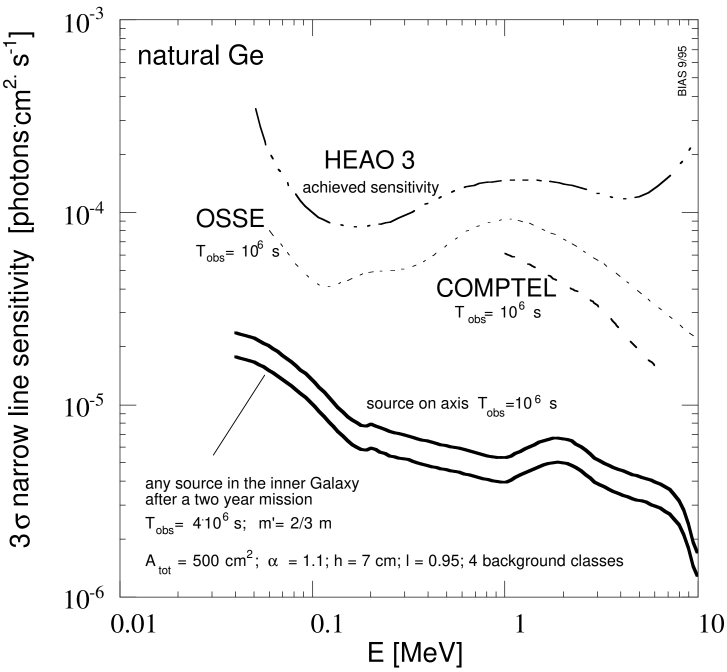

Fig. 5. Estimated 3σ narrow line sensitivity for the INTEGRAL Spectrometer

4. Conclusion

With its expected performances SPI will certainly have a quite significant impact in the nuclear astrophysics domain. Moreover, associated with IBIS the other main instrument aboard INTEGRAL which has a better angular resolution and a higher continuum sensitivity below 1 MeV, the physical properties of X binaries including a compact object (neutron star or black hole) will be better approached. The XRM working to few keV will allow for the first time to observe simultaneously the sources from soft X rays to gamma rays of few MeV. For X binaries, AGN, … which are in general quite variable, this facility will be of the highest scientific interest.

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