ELSEVIER

Nuclear Instruments and Methods in Physics Research A 422 (1999) 139–143

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Development of large volume organic scintillators for use in the MASCO telescope

Flavio D'Amico[a,*], Margarida Mizue Hamada[b], Carlos Henrique de Mesquita[c], José Mauro Vieira[b], Nélson Pereira da Costa Jr.[b], Thyrso Villela[a], João Braga[a]

[a] *Instituto Nacional de Pesquisas Espaciais,INPE, Av. dos Astronautos 1758, 12227-010 S.J. dos Campos, Brazil*
[b] *Instituto de Pesquisas Energéticas e Nucleares, IPEN, Brazil*
[c] *Instituto do Coração do HCFMUSP, Brazil*

Abstract

The development and construction of plastic scintillators of large volume, to be used as Compton suppressors in the MASCO telescope, are described. We also outline some characteristics of MASCO, which is a coded-mask gamma-ray imaging telescope with an angular resolution of 14 in a 14° (diameter, conical) field-of-view with a sensitivity of 3.92, 1.33 and 1.18×10^{-5} photons $cm^{-2}\,s^{-1}\,keV^{-1}$ in 0.05, 0.30 and 1 MeV respectively, for an integration time of 6 h and a residual atmosphere of 3.5 g cm^{-2}. The Compton supressor described contains 12 modules of plastic scintillators, each one built as a trapezoidal prism (1 m of length) with a cross section with sides of $14 \times 22\,cm^2$ and 15 cm thick (27 l of volume). Measurements of transmittance, luminescence, X-ray fluorescence and light output were carried out with the purpose of characterizing the detector. We present the estimates of the imaging sensitivity and the sensitivity for pulsed sources of the MASCO instrument.

1. Introduction

The minimum flux that can be measured from celestial γ-ray sources is limited by the sensitive area of the telescope employed, the integration time and the level of the instrumental background rate. Current state-of-the-art hard X-ray and γ-ray telescopes are still obliged to operate in conditions of intrinsically low signal-to-noise ratio and it is vital to use techniques to reduce the background level, improving the final sensitivity. These techniques frequently use segmented or different types of detectors.

In this work we describe the construction of large volume organic scintillators used as Compton suppressors in the MASCO telescope [1,2], following the same approach used in the GRIP telescope [3]. The use of scintillators as Compton suppressors, operating in anticoincidence with the main detector, is a very efficient way of reducing background in a γ-ray detector. This method avoids both the large weight and the internal γ-ray production of passive absorbing material such as lead.

* Corresponding author. Tel.: 55 12 3456745; fax: 55 12 3456750; e-mail: damico@das.inpe.br.

0168-9002/99/$ – see front matter
PII: S0168-9002(98)01089-4

We show characterization tests and light attenuation γ-ray curves of two different types of detectors. We also give a brief description of the MASCO telescope. We conclude this work presenting the MASCO's imaging sensitivity and the sensitivity of the telescope for pulsed signals.

2. The MASCO telescope

The MASCO telescope is fully described elsewhere [1,2,4,5]. Here only the main aspects of the detector imaging system are outlined.

MASCO is an imaging telescope that employs the coded-aperture technique [6] (for a review see Ref. [7]). We use as position sensitive detector (PSD) a 16″ diameter 2″ thick NaI(Tl) with 19 PMTs optically coupled in an Anger camera configuration. The size of the basic mask cell is 1.25 cm, the mask size is 100 cm (diameter) and the mask-PSD separation is 305 cm. These numbers fix some key properties of the telescope: an angular resolution of 14′ and a fully coded field of view (FOV) of 14° (diameter, conical). The mask is built based on a 19×19 modified uniformly redundant array (MURA). The MURAs [8] are a new class of patterns that can be used to build masks with the same optimal characteristics of the URAs [9].

MASCO employs a large number of scintillation detectors. For charged particles veto (directly above the PSD) a 3 mm thick organic scintillator is used. At the bottom it is used another NaI(Tl) identical to the PSD. On the sides 12 modules of large volume organic scintillators is used. Our estimated sensitivities are 3.92, 1.33 and 1.18×10^{-5} photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}\,\mathrm{keV}^{-1}$ in 50, 300 keV and 1 MeV, respectively, for an integration time of 6 h, a residual atmosphere of 3.5 g cm^{-2} and a $3\,\sigma$ confidence level. Due to its angular resolution, FOV and sensitivity (described in more details in Section 4) MASCO is a medium sensitivity pointing instrument able to image crowded source fields. Thus (and also due to the favorable geographical position of Brazil) our main scientific target for a first flight is the Galactic Center region. A $\sim 10^{\circ} \times 10^{\circ}$ field centered in Sgr A contains 10 γ-ray sources with a high degree of spectral and temporal variability [10], result of a complex phenomenology not yet completely understood.

3. Construction and tests of the plastic scintillators

Large volume plastic scintillators of 1.20 m of length with a trapezoidal cross section with sides of 19 and 29 cm and 19 cm thick (551 of volume) were produced by polymerization of styrene monomer solutions, containing 0.4% of 2,5-diphenyloxazole (PPO) and 0.04% of 1,4-bis(5-phenyloxazol-2-yl) benzene (POPOP). The commercial styrene monomer was previously purified, immediately before use, by repeated vacuum distillation, until the aimed purity was reached, at a pressure of 10 mm Hg at about 31°C. The effectiveness of purification was evaluated by transmittance measurements in the wavelength range 300–800 nm. The polymerization was induced by two ways:

1. *Heating at low pressure*: The stainless steel metallic mold containing the PPO and POPOP solution in monomer styrene was vacuum sealed and placed in a thermostatically controlled furnace at 25°C. The temperature was gradually increased until reaching 90°C in a period of 30 d. After that, the temperature was raised to 120°C for 1 d and reduced slowly to about 30°C in steps of 1°C/h.
2. *Using chemical catalyst*: To the same solution (described above) we added 0.01% of catalyst 1,1-bis(terc-peroxybutyl)cyclohexane (TRIGONOX22-C-50) from Akzo Ltd. The polymerization of this solution was carried out in the aluminum metallic mold at 80°C. After one day a solid product was obtained, but we still kept it at the temperature of 80°C during one week, followed by a heating of 120°C for 1 d and a slow decrease to room temperature (in steps of 1°C/h).

The transmittance of two samples of the plastic scintillators were measured for a thickness of 10 mm, in the spectral region from 200 to 800 nm. The evaluation of the luminescence emission spectra was carried out in the range from 200 to 800 nm. The γ-rays from a ^{137}Cs source were used

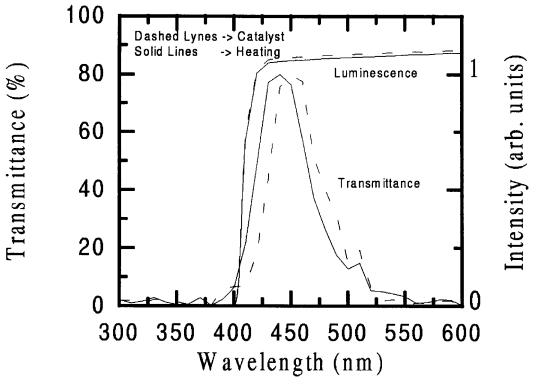

Fig. 1. Luminescence and transmittance spectra of the two different types of plastic scintillators.

to excite the crystals. Fig. 1 shows the transmittance and luminescence emission spectra of the plastic scintillators manufactured by the two processes. No significant difference was observed for both plastic scintillators. The wavelength for maximum luminescence was 425 nm. The optical transmission reached, in the range of the luminescence, was about 80%. These results have shown a suitable superposition of the transmission capacity of these scintillators in the luminescence region. The measured refractive indexes, were 1.51 ($\pm$ 0.1) and 1.58 ($\pm$ 0.1), for plastic polymerized by heating and with catalyst, respectively. The densities of the plastic scintillators are of 1.08 ($\pm$ 0.1) g cm^{-3} and 1.04 ($\pm$ 0.2) g cm^{-3}. The softening temperature for the two plastic scintillators were 83°C. The chemical impurities in the plastic scintillators (Al, Cu, Si, Mn, Zn, Ni, Cr, Fe, P and S), from the metallic mold contamination, were evaluated using a Rigaku-Denki X-ray fluorescence spectrometer. The metallic contaminants found in the analysis of the plastic scintillators were under the minimum detectable quantity for this technique. In this analysis no chemical elements originated from the molds were found in a concentration that could influence the optical quality of the detectors. For the pulse height measurements, the samples were directly coupled to an Amperex XP2202B bi-alkaline photomultiplier and excited by a ^{137}Cs γ-ray source placed on top of the scintillator. The pulse heights were collected by a multichannel analyzer and the relative light output was evaluated by comparison of the pulse height. No significant difference was observed in two spectra. The luminescence decay time was 2.78 ($\pm$ 0.09) ns for the plastic scintillators polymerized by heating, while for that produced using catalyst was 3.37 ($\pm$ 0.18) ns, showing a difference between the scintillators. This difference is not so significant in using the scintillators in an anticoincidence system with a NaI(Tl). The decay time can be quite sensitive to impurity originated from the catalyst, initiators and desmolding.

We have also performed light attenuation γ-ray curves for the two different types of modules. These tests were performed after modules's mechanical machining processes with the modules in their final dimensions and format (a trapezoidal prism 1 m length, sides 14 and 22 cm and 15 cm thick). We conducted a simple test to verify the ability of the modules to give a measurable signal, in response of a γ-ray photon, as a function of the distance to the PMT. Due to the thickness of the modules, they act as passive collimators for X-ray photons up to $\sim$ 150 keV. We could also verify with this test the threshold energy of our anticoincidence electronic circuit. A simple mechanism was built to place a ^{137}Cs collimated source in one of the sides and then shift it in steps of 5 cm. With the aid of a MCA we could derive the pulse height produced by the two modules as a function of the source-PMT distance. The γ-ray light curves are presented in Fig. 2. The data points were fitted (and the best fit is a simple exponential) using the ANACOMP code [11]. The error bars were obtained following standard procedures [12]. In general, the two different modules have a very similar behaviour. We could also verify that our threshold energy is $\sim$ 60 keV (see details in Ref. [4]).

The characterization results show that there is no quality change in most of the parameters for the scintillators produced by the two processes. However, to produce large plastic scintillators, the thermal polymerization at low pressure presents some disadvantages, such as difficulties in the manufacturing process, due to the formation of bubbles and crashes during the polymerization, the difficulty reproducing in their characteristics and also the difficulties in maintaining the operational conditions for a long period.

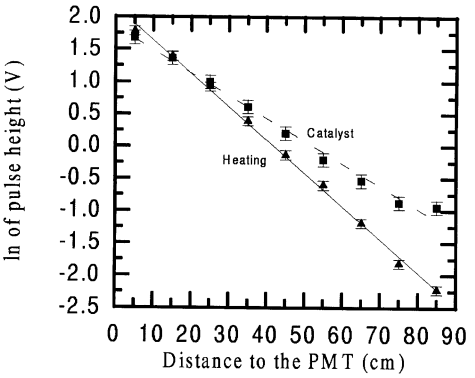

Fig. 2. Gamma-ray light attenuation curves for the two plastic scintillators.

4. MASCO sensitivity

The sensitivity of a γ-ray telescope can be calculated using (see Ref. [13]):

$$F_{\min} = \frac{k}{2\,A_{\text{eff}}\,\Delta E}\sqrt{\frac{8\,B}{T}}, \tag{1}$$

where k is the confidence level (number of σ), A_{eff} the effective area (in cm^2), ΔE the energy band (in keV), B the background rate (in counts/s) and T the integration time (in s). In this sense $F_{\min}$ has to be interpreted as the minimum source flux detectable for the telescope in T seconds integration time with a k-sigma detection level. To estimate the MASCO sensitivity we must have some idea of the expected background rate. In estimating the TIMAX sensitivity [14] we have done this by comparison with the EXITE (see, e.g., Ref. [13]) telescope and the results are quite good (see Refs. [15,16]). Thus we followed the same approach, estimating the MASCO expected background rate by comparison with the GRIP telescope. For a 3σ detection level, a 6 h integration time and a residual atmosphere of $3.5\,\text{g}\,\text{cm}^{-2}$, the sensitivities are of 3.92, 1.33 and 1.18×10^{-5} photons $\text{cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}$ in 50, 300 keV and 1 MeV, respectively. In estimating these sensitivities we have taken into account a 35% factor of sensitivity reduction due to our finite PSD resolution (see Refs. [7,13]). As a matter of fact we have verified this reduction factor in the MASCO's first laboratory images [4,5].

We have also investigated the sensitivity of MASCO for pulsed sources. For a pulsed (sinusoidal) signal in a background-limited regime of observation the signal-to-noise ratio (SNR) is given by (see, for e.g., Ref. [17]):

$$\text{SNR} = s\sqrt{\frac{T}{B}}, \tag{2}$$

where s is the sinal strength, T the time of observation and B the background. Following the approach described in Ref. [18], we can rewrite s as (see Ref. [4]):

$$s = \frac{(F_{\text{ave}} f A_{\text{eff}}\,T)^2}{4\,B\,P}, \tag{3}$$

where F_{ave} is the average source flux (in photons $\text{cm}^{-2}\,\text{s}^{-1}$) in a given band, f is the pulsed fraction of the signal of the source and P the period. Thus we can write

$$T = \left\{\frac{4\,P\,B^{3/2}(\text{SNR})}{(F_{\text{med}} f A_{\text{eff}})^2}\right\}^{5/2}, \tag{4}$$

and compute the time of observation required to distinguish the pulsed signal of the source for a given SNR. A source like GX 1 + 4 ($f\sim0.8$) is detected with a $20\,\sigma$ level with only ~700 s of observation with MASCO.

5. Conclusions

We have constructed large volume plastic scintillators for use in a γ-ray imaging telescope. We have conducted characterization tests for two different types of modules, and no significant difference was found in their characterisitics. Particularly one of the main parameters for our application (the transparence) was found to be fairly stable (see Fig. 2). The plastic scintillators are used as Compton supressors in MASCO. With a threshold energy for the anticoincidence system of ~60 keV, the integrated expected background counting rate for MASCO in the 50 keV to 1 MeV energy range is of $\sim230\,\text{counts}\,\text{s}^{-1}$. With this background level we perform an estimative of the imaging sensitivity of

the telescope showing that (and also due to the FOV and angular resolution) MASCO is able to image crowded source fields, like the Galactic Center region.

Acknowledgements

We are very grateful to Wilson Aparecido Calvo, Eduardo Araújo Pavão, Luiz Gonzaga de Arantes and Edson Rodrigues da Silva for invaluable technical support. We thank FAPESP (grants 93/2996-0, 95/8427-3 and 96/7638-3) and also CNPq (grant 401113/90-6-FA) for providing financial support. This work was supported by FAPESP Grants 97/14167-0 and 98/01652-0.

References

[1] T. Villela et al., Astrophys Space Sci. 214 (1994) 161.
[2] T. Villela et al., Adv. Space Res. 15 (1995) 95.
[3] M.H. Finger, Ph.D. Thesis, California Institute of Technology, USA, 1987.
[4] F. D'Amico, Ph.D. Thesis, Instituto Nacional de Pesquisas Espaciais, Brazil, 1997.
[5] J. Braga, et al. Nucl. Instr. Meth. A. 1998, submitted.
[6] R.H. Dicke, Astrophys. J. 153 (1968) 101.
[7] E. Caroli et al., Space Sci. Rev., 45 (1987) 349.
[8] S.R. Gottesman, E.E. Fenimore, Appl. Opt. 28 (1989) 4344.
[9] E.E. Fenimore, T.M. Cannon, Appl. Opt., 17 (1978) 337.
[10] A. Goldwurm et al., Astron. Astrophys. 310 (1996) 857.
[11] C.H. Mesquita, Anacomp Software Manual, IPEN, Brazil, 1994.
[12] P.R. Bevington, D.K. Robinson, Data Reduction and Error Analysis for the Physical Sciences, 2nd ed., McGraw-Hill, New York, 1992.
[13] J. Braga, Ph.D. Thesis, University of São Paulo, Brazil, 1992.
[14] J. Braga et al., Exp. Astrophys. 2 (1991) 101.
[15] J. Braga et al., Exp. Astrophys. 5 (1994) 269.
[16] J. Braga et al., Adv. Space Res. 15 (1995) 157.
[17] D. Chakrabarty, Ph.D. Thesis, California Institute of Technology, USA, 1996.
[18] J. Middleditch, Ph.D. Thesis, Universisty of California, USA, 1976.