Radiation Physics and Chemistry 153 (2018) 140–151

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

On the design of experiments based on plastic scintillators using GEANT4 simulations

G. Ros[a], G. Sáez-Cano[a], G.A. Medina-Tanco[b], A.D. Supanitsky[c]

[a] Dpto. Física y Matemáticas, Universidad de Alcalá, Alcalá de Henares, Spain
[b] Instituto de Ciencias Nucleares, UNAM, México D. F., Mexico
[c] Instituto de Astronomía y Física del Espacio, CONICET-UBA, Buenos Aires, Argentina

ARTICLE INFO

Keywords:
Plastic scintillator
Geant4 simulations
Coating
Pulses
Efficiency

ABSTRACT

Plastic scintillators are widely used as particle detectors in many fields, mainly, medicine, particle physics and astrophysics. Traditionally, they are coupled to a photo-multiplier (PMT) but now silicon photo-multipliers (SiPM) are evolving as a promising robust alternative, specially in space born experiments since plastic scintillators may be a light option for low Earth orbit missions. Therefore it is timely to make a new analysis of the optimal design for experiments based on plastic scintillators in realistic conditions in such a configuration.

We analyze here their response to an isotropic flux of electron and proton primaries in the energy range from 1 MeV to 1 GeV, a typical scenario for cosmic ray or space weather experiments, through detailed GEANT4 simulations. First, we focus on the effect of increasing the ratio between the plastic volume and the area of the photo-detector itself and, second, on the benefits of using a reflective coating around the plastic, the most common technique to increase light collection efficiency. In order to achieve a general approach, it is necessary to consider several detector setups. Therefore, we have performed a full set of simulations using the highly tested GEANT4 simulation tool: several parameters have been analyzed such as the energy lost in the coating, the deposited energy in the scintillator, the optical absorption, the fraction of scintillation photons that are not detected, the light collection at the photo-detector, the pulse shape and its time parameters and finally, other design parameters as the surface roughness, the coating reflectivity and the case of a scintillator with two decay components. This work could serve as a guide on the design of future experiments based on the use of plastic scintillators.

1. Introduction

Plastic scintillation detectors have been used in several fields for decades. As a tracker or calorimeter in nuclear and high energy physics thanks to their fast time response, high efficiency for charged particles, ease to manufacture, versatility and moderate costs. As an example, they have been recently selected for MINOS (Adamson, 1998), OPERA (OPERA Collaboration, 2000) and AugerPrime (The Pierre Auger Collaboration), the extension of the Pierre Auger Observatory. A complete review on the use of scintillators in particle physics can be found in Kharzheev (2015). Plastic scintillators can be exposed to high levels of radiation which along with their simplicity, low density and large volume compared to solid state based systems makes them also suitable for astrophysical purposes. Thus, plastic scintillators have been used as particle or neutron spectrometers in planetary missions in the past such as Phobos, Lunar Prospector or Mars Odyssey and, more recently, in Dawn and Solar Orbiter (for a review see Owens, 2008, AMS (von Doetinchem et al., 2009) or DAMPE, 2017). In addition, their high detection efficiency and the proportionality between the light output and exciting energy make them very useful for radiotherapy and dosimetry applications (Beddar et al., 1992).

In this study, we have selected as a source an isotropic flux of electrons and protons from 1 MeV to 1 GeV, a typical scenario in the detection of cosmic ray particles since there are three main sources of radiation at Low Earth Orbit (LEO) altitude, which are Solar Event Particles, Trapped protons and electrons and Galactic Cosmic Rays. As an example the integral flux of trapped protons at LEO is shown in Fig. 1. However, this selection is also of interest for any of the fields of application of plastic scintillators such as electron (Hogstrom and Almond, 2006) or proton (Newhauser and Zhang, 2015) beam therapies or in case of hadronic calorimetres in particle physics as, for example, in CMS (1997).

We center on two issues of general interest, i.e., how, for a fixed photo-detector area, the increase of the plastic volume and the use of a

E-mail address: german.ros@uah.es (G. Ros).

https://doi.org/10.1016/j.radphyschem.2018.09.021
Received 15 May 2018; Received in revised form 19 September 2018; Accepted 24 September 2018
Available online 25 September 2018

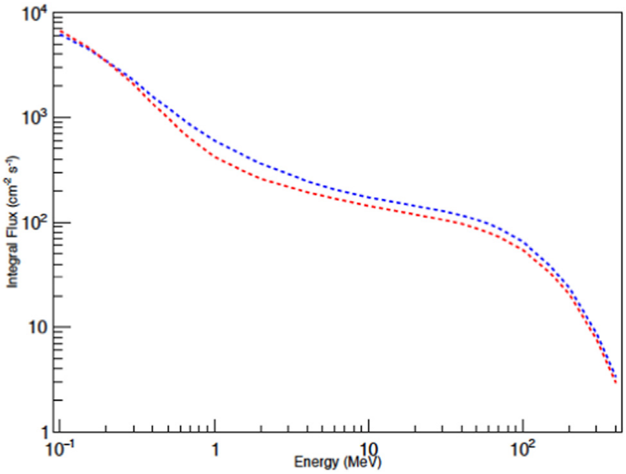

Fig. 1. Integral flux of trapped protons in solar maximum (red) and minimum (blue) for a typical low earth orbit akin to the ISS (obtained using SPENVIS simulation code (SPENVIS)).

reflective coating around the plastic could affect the capabilities of the experiment. The former is specially important in space experiments where the mass is a critical point. The latter is the most common technique to increase the light collection efficiency for a given volume, the key point in most of these experiments.

In the literature, the effect of the scintillator volume has been previously analyzed in the medical area (dossimetry, radiotherapy) in case of plastics using a beam of cobalt-60 radiation (electrons of 315 keV and gammas of ~ 1 MeV) (Archambault et al., 2005) but also in liquid scintillators radiated with electrons and protons in the MeV range (Galloway and Savalooni, 1982) and with pure simulations (Ghal-Eh, 2011), but as far as we know it has not been analyzed in the astrophysical scenario of a space mission where the energy input covers an extended spectrum and the mass is a critical issue. The effect of the reflective coating has also been analyzed in Adamson (1998), Dyshkant et al. (2006), Riggi et al. (2010) and a general discussion could be found in Kharzheev (2015). However, most of the results are based on experimental setups with different geometries, scintillators, primary beams and photo-detectors. Therefore, the comparison between the results of these studies is not trivial. Alternatively, we have used the GEANT4 simulation tool (Agostinelli et al., 2003) to consider a more general approach. GEANT4 allows to track photons inside the medium and to take into account all the optical properties of scintillators and its coating (emission, absorption, reflection, refraction, etc.). Furthermore, it has been demonstrated that GEANT4 realistically describes the response of plastic scintillation in space physics (Espirito-Santo et al., 2004), particle physics (Kohley, 2012; Li-Ming, 2004) or dossimetry (Guimaraes et al., 2008).

2. Simulation setup

2.1. Geometry and material properties

We want to study the influence on light collection efficiency of the ratio between the volume of the plastic scintillator and the area of the photo-detector in contact with it. We assume the photo-detector as a silicon parallelepiped of 1 cm width and a contact area with the scintillator of $L \times L$, taking $L = 2$ cm. It is located in one face of the plastic which is a cube whose volume is $(F \times L)^3$, where F is the scale factor whose values will be $F = 1, 3, 10$. The setup is shown in Fig. 2. If a photon crosses the interface between the plastic scintillator and the photo-detector it is considered as *detected* and then its propagation is terminated.

Organic plastic scintillators have been widely produced using

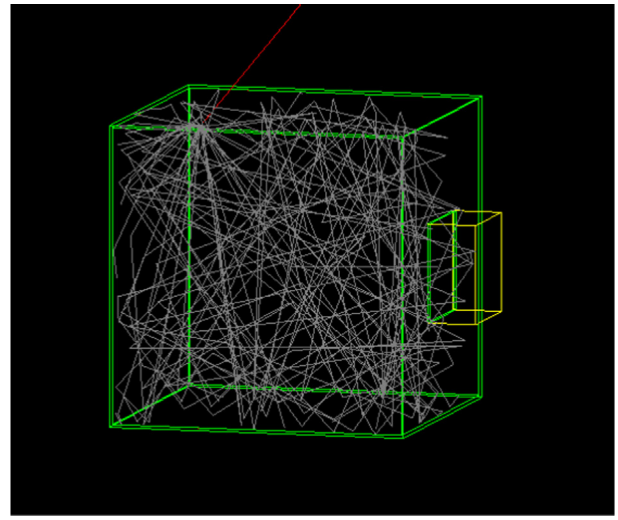

Fig. 2. Setup for the simulation. The case for $F = 3$ is shown. The green and yellow boxes represent the plastic scintillator and the photo-detector respectively, the red line is the incoming particle (1 MeV electron in this case) and the gray lines are the scintillation photons produced.

different techniques that lead to different plastic properties. These methods include the bulk polymerization method which achieves the highest transparency and uniformity but with high cost and manufacture time, injection molding that is highly productive (used at ATLAS and LHCb), the molding method (also used at CERN experiments), the extrusion method where plastic is produced using mechanically extruded polystyrene pellets (developed at Fermilab for MINOS (Adamson, 1998)). A detailed description could be found in Kharzheev (2015). In addition, a novel method based on the technology of photosensitivity rapid prototyping has been developed recently, which requires a shorter manufacture time, reduces the cost and allows to use the 3D printing technology (Zhu et al., 2016a).

We have selected the plastic developed at Fermilab for our simulation setup since the extrusion method has been recently improved for MINERVA (Aliaga et al., 2014) and these plastics are widely used and tested in several cosmic ray experiments such the Pierre Auger Observatory (Supanitsky et al., 2008) and BATATA (Alfaro et al., 2010). It is an extruded scintillator with a co-extruded reflective coating, whose manufacturing process has been optimized for higher light yield and lower costs. The base material in the plastic scintillates in the UV, but the mean free path of those photons is only a few millimeters, therefore, a wavelength shifter, also called 'fluor', needs to be added to the material. Thus, the scintillator is infused with two dopants, PPO and POPOP. The choice of the fluors is largely dictated by their emission and absorption spectra. Fluor absorption spectrum should be close to the base emission spectrum. The maxima of the wavelength shifter absorption and emission spectra should be as far away from each other (Stokes shift) as possible to avoid self absorption of emitted photons. The transmission achieved is more than 85% in the spectral range of interest (Plau-Dalmau et al.). In addition, PPO and POPOP are a great choice for polystyrene-based plastic scintillators in order to achieve higher intensity and light yield if their concentration is properly tuned for each plastic (Zhu et al., 2016b). Thus, their concentration was optimized to be 1% and 0.03% by weight for PPO and POPOP respectively for the scintillator assumed here (Aliaga et al., 2014). The emission spectrum of the extruded plastic with these dopants is shown in Fig. 3. The other properties of the plastic scintillator considered in the simulation are shown in Table 1.

As previously mentioned, the scintillator is covered with a co-extruded reflective coating that is applied simultaneously with the extrusion of the scintillator. Thus, pellets of TiO_2 were mixed with polystyrene pellets. This method reduced significantly the costs and