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Radiation damage effects on the optical properties of plastic scintillators

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ABSTRACT

We report on the radiation damage to the optical properties of plastic scintillators following irradiation using a 6 MeV proton beam produced by the 6 MV tandem accelerator of iThemba LABS, Gauteng. A comparative is drawn between polyvinyl toluene based commercial scintillators EJ200, EJ208, EJ260 and BC408 as well as polystyrene based scintillator UPS923A and scintillators manufactured for the Tile Calorimeter. Results on the proton induced damage indicate a reduction in the light output and transmission capability of the plastics. Scintillators containing a larger Stokes shift, i.e. EJ260 and EJ208 exhibit the most radiation hardness. The EJ208 is recommended as a candidate to be considered for the replacement of Gap scintillators in the Tile Calorimeter for the 2018 upgrade.

1. Introduction

Plastic scintillators are organic materials that luminescence when interacting with ionising radiation. The incident radiation causes electronic excitations with the scintillating material. As the material relaxes and the electrons return to ground state, the scintillator fluoresces and emits light. The emitted light is dependent on the energy of the incident particle. Energy is dissipated as the charged particle travels through the scintillator. The dissipated energy results in the formation of ions and free radicals that affect the scintillators ability to emit light and also causes structural damage within the molecule.

The plastic scintillators consist of organic flours that are suspended in a polymer base. The base contains some form of aromatic ring structure that gives rise to a delocalized π-electron structure within the molecule. When exposed to ionising radiation, absorption occurs in the visible and ultra-violet regions that correspond to the excitation of the singlet π-electron state. Radiationless internal conversion occurs at excitations in higher states that de-excite to lower states of the same multiplicity within a short time period of $\sim 10^{-12}$ s.

When vibrational modes of two excited states overlap, additional vibrational energy is created by the excitations. This overlap is a result of processes such as phosphorescence due to the population of the triplet states or radiationless internal conversion amongst others. The self-absorption of the scintillation light can be prevented by adding small concentrations of primary flours to the plastic polymer. The primary flours act as an agent to keep the plastic scintillator transparent to its own scintillation light. Secondary flours are added to act as wavelength shifters to ensure that the wavelength of the light leaving the scintillator is detected by optical fibers that are connected to the photomultiplier tubes [1].

Plastic scintillators are employed within high energy particle detectors due to their properties such as high optical transmission and fast rise and decay times [1]. The generation of fast signal pulses enables efficient data capturing. Compared to inorganic crystals, plastic scintillators are easy to manufacture and therefore cost effective when covering large areas such as the ATLAS detector [2]. However, the challenge faced with using plastic scintillators in detectors is the damage incurred due to their interactions with ionising particles. The damage results in a significant decrease in the light yield of the scintillator and errors are introduced in the data captured.

2. Materials and methods

Four commercial plastic scintillators (EJ200, EJ208, EJ260 and BC408) and two types employed by the ATLAS detector (UPS923A and TileCal) were investigated. Details on their composition and properties are listed in Table 1 [3–6].

Proton irradiations of plastic scintillator samples were conducted using the 6 MV (operated at 3 MV) Tandem Accelerator at

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Table 1
Summarising the various properties of the scintillators under study.

Scintillator	EJ200	EJ208	EJ260	BC408	UPS923A	TileCal
Manufactured by:	Eljen Technology	Eljen Technology	Eljen Technology	Saint Gobain Crystals	Institute of Scintillating Materials	Institute of High Energy Physics (IHEP)
Base	PVT	PVT	PVT	PVT	PS	PS
Primary Fluor	0.3%	0.3%	0.3%	Not available (However, listed as a	2% PTP	1.5% PTP
Secondary Fluor	organic fluors	organic fluors	organic fluors	performance equivalent of EJ200)	0.03% POPOP	0.044% POPOP
Light Output,% Anthracene	64	60	60	64	60	Not available
Wavelength of Max. Emission, nm	425	435	490	425	425	
Rise Time, ns	0.9	1	~	0.9	0.9	
Decay Time, ns	2.1	3.3	9.2	2.1	3.3	

iThemba LABS, Gauteng. Irradiation was conducted on samples polished to dimensions of 5 mm by 5 mm and of 350 ± 30 μm thickness. The samples were mounted on a hexagonal carousal sample holder and housed within a nuclear microprobe chamber under vacuum conditions. The proton beam was passed through an object slit and collimator slit and a set of magnetic quadrupole triplets were used to focus the beam onto a sample with a spot size of ~20–30 μm.

The beam was scanned in the x and y plane using a raster pattern to achieve a uniformly irradiated area of approximately 1.8 mm by 1.8 mm. This irradiation technique was required because using a large diameter beam which is not scanned over the sample resulted in an inhomogeneous intensity distribution of a Gaussian shape which was not conducive to the required damage analysis techniques. This procedure for proton irradiations has been previously described in [7,8]. Fig. 1 shows a schematic representation of the tandem accelerator at iThemba LABS.

The beam current was determined by measuring the current generated across a metal plate situated on the side opposite to the sample on the carousal. The beam current, integrated per second, was recorded for the duration of each irradiation. Two samples of each plastic scintillator type were irradiated per dose for targeted doses of 0.8 MGray, 8 MGray, 25 MGray and 80 MGray.

The effects of radiation damage on the optical properties of the samples were characterised by conducting light transmission and light fluorescence studies. Transmission spectroscopy was conducted using the Varian Carry 500 spectrophotometer. Light transmission was measured relative to transmission in air over a range of 200–800 nm. Transmission spectra were collected prior to irradiation as well as 1 day, 2 days, 1 week and 4 weeks after for each sample, and the relative loss was gauged.

The light fluorescence of the proton irradiated plastic scintillators was measured using the LabRAM HR Raman spectrograph. A 229 nm laser with a power of ~3–5 mW was employed to provide energy for molecular excitations to occur and thereby prompt light emission through luminescence. Photo-bleaching was reduced by scanning the laser over a 20 × 20 μm^2 area and limiting the acquisition time to one second per spot tested. Three spots along the irradiated region and three spots along the un-irradiated regions of each sample were tested in order to gauge the ratio of loss to fluorescence yield over the wavelength range of 350–500 nm.

3. Results and discussion

After irradiation, samples obtained a yellow to brown discolouration as dose exposure increased. After removal from the microprobe, samples were exposed to air and a fading of the discolouration was observed. For the 800 kGy irradiated samples, the fading occurred within several minutes from removal. The

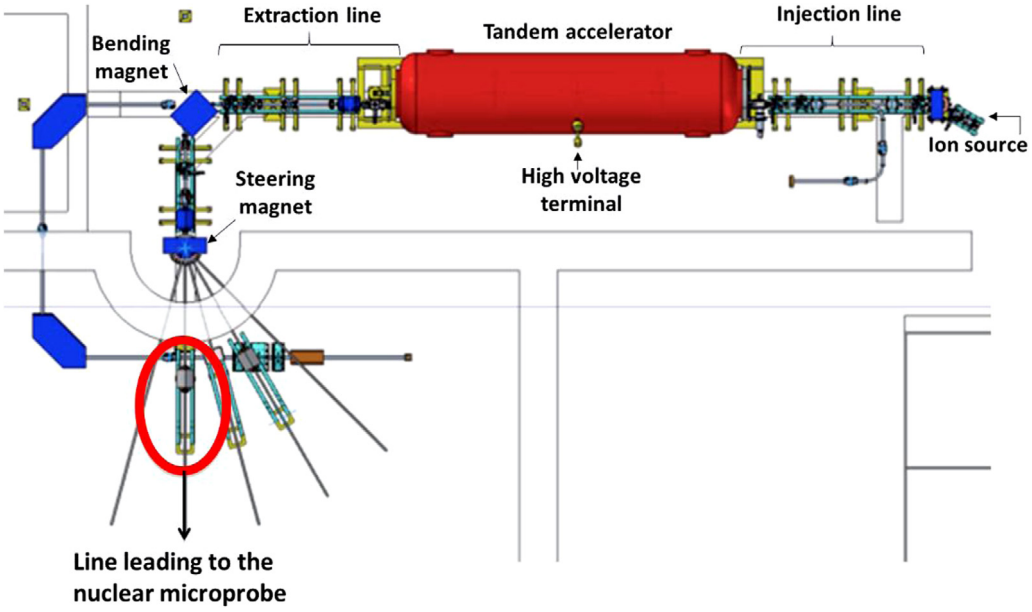

Fig. 1. Schematic representation of the tandem accelerator at iThemba LABS.

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