Nuclear Inst. and Methods in Physics Research B 436 (2018) 236–243

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

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

Effects of neutron radiation on the optical and structural properties of blue and green emitting plastic scintillators

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A R T I C L E I N F O

Keywords:
Neutron radiation
Neutron fluence
Radiation damage
Scintillator
Polystyrene

A B S T R A C T

We report on the optical and structural properties of plastic scintillators irradiated with neutron beams produced by the IBR-2 reactor of the Frank Laboratory of Neutron Physics in JINR, Dubna. Blue UPS-923A and green plastic scintillators were irradiated with neutron fluence ranging from 10^{13} to 10^{17} n/cm^2. Discolouring in the plastic scintillators was observed after irradiation. The effects of radiation damage on the optical and structural properties of the samples were characterized by conducting light yield, light transmission, light fluorescence and Raman spectroscopy studies. The results showed that neutron radiation induced damage in the material. The disappearance of the Raman peak features in green scintillators at frequencies of 1165.8, 1574.7 and 1651.2 cm^{-1} revealed significant structural alterations due to neutron bombardment. Losses in fluorescence intensity, light yield and light transmission in the plastic scintillators were observed.

1. Introduction

Plastic scintillators are employed within high energy particle detectors due to their desirable properties such as high optical transmission and fast rise and decay times [1]. The generation of fast signal pulses enables efficient data capturing. They are used to detect the energies and reconstruct the path of the particles through the process of luminescence due to the interaction of ionising radiation. Compared to inorganic crystals, plastic scintillators are organic crystals that are easily manufactured and therefore cost effective when covering large areas such as the ATLAS detector [2].

In the ATLAS detector of the Large Hadron Collider (LHC), there is a hadronic calorimeter known as the Tile Calorimeter that is responsible for detecting hadrons, taus and jets of quarks and gluons through the use of plastic scintillators. These particles deposit large quantities of energy and create an immensely detrimental radiation environment. The neutrons mostly coming from the shower tails contribute to the counting rates and degradation of plastic scintillators through neutron capture. Monte-Carlo calculations have been performed to estimate doses and particle fluences currently experienced at different regions of the detector, operating at a nominal luminosity of 10^{34} cm^{-2}s^{-1}. The maximum neutron fluence per year in the Tile Calorimeter barrel was estimated at around 10^{12} n/cm^{2}yr [3]. The LHC intends to increase its luminosity by a factor of up to ten times by 2022, and this will drastically impact the radiation environment in the ATLAS detector.

The interaction of ionising radiation with plastic scintillators results in the damage of these plastic scintillators. According to Sonkawade et al. [4], during irradiation the properties of scintillators are altered significantly depending on the structure of the target material, fluence and the nature of radiation. Some of these structural modifications have been ascribed to the scissoring of the polymer chain, intensification of cross-linking, breakage of bonds and formation of new chemical bonds. This damage results in a significant decrease in the light yield of the scintillator and as a result, errors are introduced in the data captured.

Studies on proton irradiated plastic scintillators conducted by the Wits High Energy Physics (Wits-HEP) group have been reported in

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https://doi.org/10.1016/j.nimb.2018.10.002
Received 27 August 2018; Received in revised form 3 October 2018; Accepted 3 October 2018

Table 1
Properties of the scintillators under study.

Scintillator	Blue UPS-923A	Green
Manufacturer	Institute for Scintillation Materials	Institute for Scintillation Materials
Base	Polystyrene	Polystyrene
Primary fluor	2% PTP	3HF
Secondary fluor	0.03% POPOP	
Light Output (% Anthrance)	60	
Wavelength of Max. Emission (nm)	425	530
Rise time (ns)	0.9	0.9
Decay time (ns)	3.3	7.6

literature [5–7]. This paper extends the study to focus on the effects of non-ionising radiation (i.e. neutrons). Compared to the interaction of ionising radiation, the interaction of non-ionising radiation with matter is more interesting since the particles interact indirectly with the atoms of the material. When materials are bombarded with neutrons, collision cascades are created within the material that results in point defects and dislocations. A Primary Knock-on Atom (PKA) is created when the kinetic energy from the collision is transferred to the displaced lattice atom. The knock-on atoms lose energy with each collision and that energy in turn ionizes the material [8]. Neutron irradiation allows for bulk probing on materials since they are highly penetrating particles.

2. Experimental details

Commercial blue scintillators UPS-923A [9] and recently synthesized green scintillators [10,11] were investigated. The samples were prepared at the Institute for Scintillation Materials (ISMA, Kharkov). They were cut and polished to dimensions of 2 × 2 cm with 6 mm thickness. Table 1 has some important properties of the plastic scintillators under study.

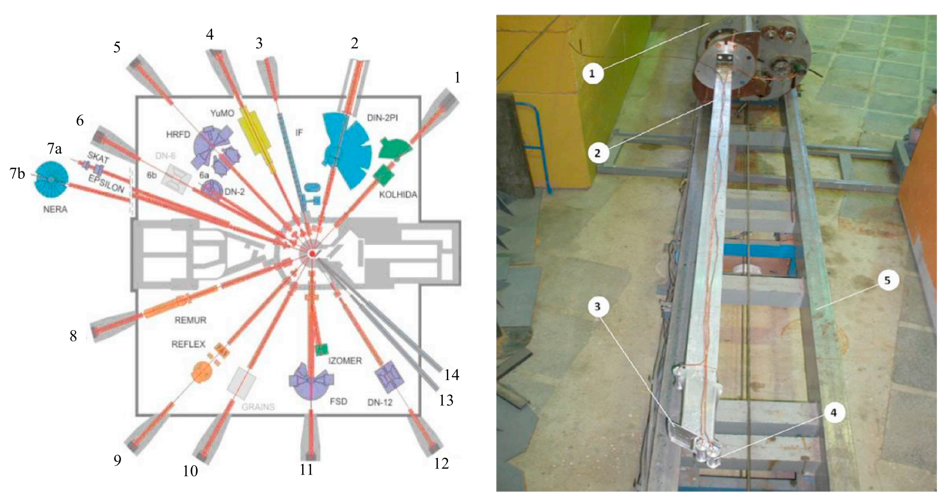
Channel number 3 of the IBR-2 reactor, as schematically shown in Fig. 1, located at the Frank Laboratory of Neutron Physics (FLNP) at the Joint Institute for Nuclear Physics (JINR) in Dubna, Russia was used to irradiate the samples [12,13].

The samples were subjected to a beam of neutrons for 432 hours, this was the duration of the reactor cycle during the October 2017 run (9–27 October 2017). The reactor operated at an average power of 1875 kW with the samples placed at various positions away from the reactor core to achieve various neutron fluences. The neutron fluence ranged approximately between 10^{13} and 10^{17} n/cm^2. However, during the irradiation only neutrons with energy $E > 1$ MeV were monitored. These neutrons account for about a quarter of the total flux. Hereafter we refer to number of fast neutrons with energy $E > 1$ MeV, although the actual amount of neutrons are a factor of four higher. As shown in Fig. 2, the discolouration of the samples is evident after irradiation.

The studies of effects of radiation damage on the optical and structural properties of the samples were characterized by conducting light yield, light transmission, light fluorescence and Raman spectroscopy measurements. Transmission spectroscopy studies were conducted using the Varian Cary 500 spectrophotometer located at the University of the Witwatersrand. Light transmission was measured relative to transmission in air over a wavelength range of 300–800 nm. The spectrophotometer consists of a lamp source and diffraction grating to produce a differential wavelength spectrum of light. A tungsten lamp was used to produce light in the visible spectrum and a deuterium lamp was used to produce light in the ultra-violet spectrum.

Light fluorescence measurements of the neutron irradiated plastic scintillators were conducted at the University of the Witwatersrand using the Horiba LabRAM HR Raman spectrometer. Light emission resulting from the luminescence phenomenon was excited in the plastic scintillators using a laser excitation wavelength (λ_{ex}) of 244 nm, operating at a power of ~20 mW. A laser spot size of 0.7 µm provided energy for molecular excitations to occur. A grid of 11 × 11 points (121 acquisition spots) was mapped across a surface area of 200 × 200 µm using a motorised X-Y stage. This allowed for an average representative spectrum to be determined largely free from local variations introduced by surface features such as scratches.

The light yield measurements were conducted at the European Organisation for Nuclear Research (ATLAS-experiment) using a light tight box set-up shown in Fig. 3. The plastic scintillators were excited with β-electrons emitted by a ^{90}Sr source with average energies of 0.54 MeV and 2.28 MeV. The ^{90}Sr source scanned over the sample in the X–Y direction whilst emitting radiation in the Z direction. The light emitted by plastic scintillators through fluorescence was detected by the photomultiplier tube (PMT). The signal generated by the PMT was further processed through electronics and digitized. To minimize background signals like those coming from the interaction of the β-electrons with the PMT, a light transmitter was used to transport the light produced by the scintillators to the cathode of the PMT. In addition, a light transmitter was covered with aluminum foil to impede β-electrons from the source.



(a)   (b)

Fig. 1. Layout of IBR-2 spectrometer complex (a), and the irradiation facility at the channel No. 3 of IBR-2 reactor experimental hall, the view from the external biological shield side: (1)-massive part of the irradiation facility, (2)-transport beam, (3)-metallic container for samples fastening, (4)-samples, (5)-rail way (b) [12].