High fluence neutron radiation of plastic scintillators for the TileCal of the ATLAS detector.

J E Mdhluli\textsuperscript{a,b,1}, Yu I Davydov\textsuperscript{c}, V Baranov\textsuperscript{c}, S Mthembu\textsuperscript{a}, R Erasmus\textsuperscript{a}, H Jivan\textsuperscript{a}, N Khanye\textsuperscript{a}, H Tlou\textsuperscript{a}, B Tjale\textsuperscript{a}, J Starchenko\textsuperscript{d}, O Solovyanov\textsuperscript{d}, B Mellado\textsuperscript{a} and E Sideras-Haddad\textsuperscript{a,b}

\textsuperscript{a} School of Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa.
\textsuperscript{b} DST-NRF Centre of Excellence in Strong Materials.
\textsuperscript{c} Joint Institute for Nuclear Research, Dubna, Russia.
\textsuperscript{d} Institute for High Energy Physics, Protvino 142281, Russia

E-mail: \textsuperscript{1}joyemmie@gmail.com

Abstract. We report on structural and optical properties of neutron irradiated plastic scintillators. These scintillators were subjected to a neutron beam with wide energy range of up to $10\text{MeV}$ and a neutron flux range of $1.2 \times 10^{12} - 9.4 \times 10^{14} n/cm^2$ using the IBR-2 pulsed reactor at the Joint Institute for Nuclear Research in Dubna. A study between polyvinyl toluene based commercial scintillators EJ200, EJ208 and EJ260 as well as polystyrene based scintillator from Kharkov is conducted. Light transmission, Raman spectroscopy, fluorescence spectroscopy and light yield testing was performed to characterize the damage induced in the samples. Preliminary results from the tests performed indicate no change in the optical and structural properties of the scintillators. The polystyrene based scintillators were further subjected to a higher neutron flux range of $3.8 \times 10^{12} - 1.8 \times 10^{14} n/cm^2$ using the IBR-2 pulsed reactor.

1. Introduction

The ATLAS detector is one of the four interaction points on the Large Hadron Collider (LHC) ring together with CMS, ALICE and LHCb detectors. It is used in particle physics experiments that are involved in the search for new particles through high energy proton-proton collisions at the LHC of CERN. The detector consists of six different detecting subsystems that are arranged in layers around the collision point to record the path, momentum and energy of the particles in order for the particles to be individually identified [1]. The tile calorimeter is a hadronic calorimeter within the calorimetry subsystem of the detector responsible for detecting hadrons, taus, and jets of quarks and gluons. It consists of a central barrel and 2 extended barrels with each barrel containing 64 modules that are made of a matrix of steel plates and plastic scintillator tiles sandwiched between them. The incoming jets are converted into a “shower” of...
particles by the steel plates. Thereafter, the plastic scintillator tiles absorb the energy of the particles and fluorescence to emit light. The light from the scintillators is passed through wavelength shifting (WLS) optical fibres and is detected by photomultiplier tubes. The signal is further processed using readout electronics in order to digitize the data for further analysis [2] [3].

Further plastic scintillators are found between the central and extended barrels, this area is known as the gap region. During the first run of data taking, the scintillators in the gap region were exposed to a radiation environment of up to 10 kGy/year. It is predicted that during the high luminosity (HL)-LHC run time, the scintillators in the Gap region will sustain a significantly large amount of radiation damage and will require replacement. This prediction has led to the comparative study of proton induced radiation damage on plastic scintillators conducted by H Jivan [2] [4], C Pelwan [5] and S Liao [6] where it was concluded that scintillators with larger Stokes shift, i.e. EJ260 and EJ208, exhibit the most radiation hardness.

The comparative study has been extended to a neutron irradiation and damage assessment study on plastic scintillators. Neutron interaction with matter makes the study more interesting since unlike with proton irradiation where the interaction with the plastics is through direct ionization, with neutron irradiation the interaction will be through indirect ionization. Neutron bombardment on materials creates a collision cascade within the material that results to point defects and dislocations. The collisions cause a massive transfer of kinetic energy to the lattice atom that has been displaced from its lattice site, becoming what is known as the primary knock-on atom (PKA). The knock-on atoms then lose energy with each collision and that energy therefore ionizes the material [7].

2. Experimental Procedure

Four plastic scintillator grades were under study, three of which were obtained from ELJEN Technologies and one from ISMA, Kharkov. The plastic scintillator grades under study are the EJ200, EJ208, EJ260 and the UPS-932A type. The three plastic scintillators obtained from ELJEN technologies are composed of a polyvinyl toluene base and 3% added organic fluors [1], the fourth plastic scintillator grade is the UPS-932A and is composed of polystyrene base.

Several samples of each plastic scintillator grade were cut and polished to dimensions 20 mm by 20 mm by 6 mm thickness at the Dzhelepov Laboratory of Nuclear Problems (DLNP) at JINR. Special sample holders were made to accommodate the samples for irradiation. Channel 3 of the IBR-2 pulsed reactor at the Frank Laboratory of Neutron Physics (FLNP) at JINR was used to irradiate the samples [8]. The samples were subjected to irradiation with a beam of fast neutrons with energies in the wide range of up to 10 $MeV$ for 337 hours. The reactor was operating at an average power of 1875 $kW$. The samples were placed at three different positions from the reactor core to expose them to different neutron fluences in order to achieve various doses. The neutron
Table 1. Neutron flux density, neutron fluences and doses at the various positions.

| Sample position | Flux density (n/cm²/s) | Fluence (n/cm²) |
|-----------------|------------------------|-----------------|
| 1               | $1 \times 10^6$        | $1.2 \times 10^{12}$ |
| 2               | $3.6 \times 10^6$      | $3.6 \times 10^{12}$ |
| 3               | $7.7 \times 10^6$      | $9.4 \times 10^{12}$ |

The Monte Carlo N-Particle (MCNP) 5 [9] code was used to simulate neutron transport through plastic scintillators and to determine the dose rate. The MCNP code is used to simulate neutron, photon and electron or coupled neutron/photon/electron transport. It is in 3-dimensions and is capable of tracking up to 34 particles and 4 light ions. It takes into account the absorption and the moderation of the neutrons as they travel through matter. Table 1 below shows the doses for various neutron flux density and neutron fluences. The Varian Carry 500 spectrophotometer was used to characterize the optical properties of the irradiated samples due to the damage of the neutron irradiation. The light transmission of the samples was measured relative to the transmission in air over a laser wavelength range between 200-800 nm.

The structural damage the scintillators may have undergone after irradiation were measured using the Raman spectroscopy technique. The Horiba Jobin-Yvon Raman spectrograph consists of an Argon laser used to provide a 515 nm excitation wavelength. Raman spectra were obtained for the un-irradiated control samples as well as on the irradiated samples to gauge the changes in the samples.

Fluorescence testing was measured with the aid of LabrRAM HR Raman spectroscopy setup. A laser of wavelength of 229 nm with a power ranging from $3 \sim 5$ mW was employed to provide enough energy for molecular excitation, which results in prompt light emission through luminescence. The laser is guided through a series of mirrors and optics in the setup, and is incident on the sample through the microscope aperture. As the sample fluoresces, the light emitted in the direction back up the aperture is collected by a detector and a differential wavelength spectrum is obtained.

Light yield testing was conducted at CERN. The samples were excited with a Sr-90 source that undergoes beta decay. As the sample fluoresces to emit light, the light is passed through four WLS optical fibres and detected by a PMT. The signal from the PMT is further processed through electronics and is digitized in the computer. For better contact between the sample and the fibres, profiles were placed along the sides of the sample to ensure the stability of the fibres.

3. Results and Discussion

Figure 1 shows the light transmission spectra of the EJ200. It is observed that at a wavelength of 400 nm the absorptive edge falls away completely and that the overall transmission of the grade remains unchanged even after irradiation. The transmission
loss is observed at wavelength 450 nm as this corresponds to the peak absorption wavelength of the wavelength shifting optical fibres coupled with these scintillators within the Tile Calorimeter. Even at this wavelength, there is still no change observed in the samples with increasing doses. The other scintillator grades also behave in the same manner.

Raman spectra were obtained for the various irradiated samples as well as for un-irradiated control samples. The irradiated samples maintained their structure with no additional peaks being formed and no damage was observed. Figure 1 also shows the Raman spectra of the EJ200 sample for the irradiated and un-irradiated samples with the highest neutron fluence at the top and the un-irradiated at the bottom. The other scintillator grades also behave in the same manner.

Figure 2 shows the fluorescence spectra of the EJ200 sample. Several fluorescence peak features are observed in the spectra. Peaks in the wavelength region of 300-375 nm correlate to fluorescence of the PVT/PS base. The "two-peak" feature is observed since the fluorescence is predominantly from the benzene ring structure. In the wavelength region of 375-500 nm, the fluorescence correlates to that of the fluor dopants. No change in fluorescence is observed in the spectra for the irradiated and un-irradiated samples. The other scintillator grades also behave in the same manner.

The light yield of the scintillators is also shown in figure 2. The light yield of the samples was measured by testing their response to a Sr-90 source that undergoes beta decay. This setup was aimed at mimicking what happens within the detector when the scintillators are measuring the energy of the particles. The EJ260 samples showed the lowest light yield. This can be a result of the maximum emission (490 nm) of the scintillator grade being greater than the maximum absorption (435 nm) of the wavelength shifting optical fibre coupled to it. The EJ200 and the EJ208 samples have a maximum emission of 425 nm and 435 nm respectively [10], allowing for the maximum amount of light emitted by the scintillators to be absorbed by the WLS optical fibres. From the graph below, we observe no change for all the scintillator grades.
grades with irradiation.

4. Conclusion

The radiation damage the plastics were exposed to is very low relative to that within the ATLAS detector. Thus, as observed in the results for the various tests, there was no change in the structural or optical properties of the plastics for the first set of samples that were irradiated during the April 2016 run. The study needs to be extended to higher neutron fluences.

5. Further work

During the autumn 2016 run of the IBR-2 reactor, UPS-923A scintillators were irradiated at higher neutron fluences range of $3.8 \times 10^{-12} - 1.8 \times 10^{14} \text{ n/cm}^2$. Raman Spectroscopy, Light yield measurements and Light transmission testing were performed on the irradiated samples. Light yield measurements were done at the Dzhelepov Laboratory of Nuclear Problems at the Joint Institute for Nuclear Research. The light yield decreased by $\sim 28\%$ after the neutron irradiation of $1.8 \times 10^{14} \text{ n/cm}^2$. A decrease in the light transmission was also observed from the light transmission spectrum. No evident structural changes were observed after the irradiation from the Raman spectroscopy measurements. No additional peaks were formed after irradiation. A more detailed analysis of these results is discussed in a proceedings written by Skhathisomusa Mthembu in this conference series.
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