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Neutron irradiation and damage assessment of plastic scintillators of the TileCal section of the ATLAS detector

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Abstract. Following the comparative study of proton induced radiation damage on various plastic scintillator samples from the ATLAS detector, a study on neutron irradiation and damage assessment on the same type of samples is currently being conducted. The samples were irradiated with different dose rates of neutrons produced in favourable nuclear reactions using a radiofrequency linear particle accelerator as well as the SAFARI nuclear reactor at NECSA and the IBR-2 pulsed reactor at the Joint Institute for Nuclear Research (JINR) in Dubna. The MCNP 5 code was utilized in simulating the neutron transport for determining the dose rate. Light transmission tests were performed in order to assess the radiation damage on the scintillators. In addition; light yield, Raman spectroscopy and Electron Paramagnetic Resonance (EPR) analysis will be used to characterize the samples after irradiation. The project aims to extend these studies to include radiation assessment damage of any component that processes the scintillating light and deteriorates the quantum efficiency of the Tilecal detector, namely, photomultiplier tubes, wavelength shifting optical fibres and readout electronics will also be exposed to neutron irradiation and the damage will be assessed in the same manner.

1. Introduction

The ATLAS detector is used to measure what happens in proton-proton collisions at the Large Hadron Collider (LHC) to find evidence of new physics. The tile calorimeter is part of the ATLAS detector, it is the hadronic calorimeter responsible for detecting hadrons, taus, and jets of quarks and gluons. The tile calorimeter consists of a central barrel and 2 extended barrels. Each barrel contains 64 modules that consists of a matrix of steel plates and plastic scintillators. The steel plates act as an absorber medium that converts the incoming jets into a "shower" of particles. The plastic scintillator tiles then absorb the energy of the particles and fluoresce to emit light. The light from the scintillators is passed through wavelength shifting 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 [1][2].

figure?

Between the central barrel and extended barrels there is what is referred to as the Gap region. This region contains additional plastic scintillators that are radially distributed within the 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 during the phase 2 upgrade in 2018. This prediction has led to the comparative study of

rad. type?

what is radiation damage?

proton induced radiation damage on plastic scintillators conducted by H Jivan [1][3], C Pelwan [4] and S Liao [5].

With 2018 rapidly approaching, the comparative study of proton irradiated plastic scintillators has been extended to study the effect of neutron induced radiation damage on plastic scintillators. In this paper, we report some of the results obtained from radiation damage induced by neutron irradiation.

2. Scintillation Mechanism

The plastic scintillator samples that were studied are organic scintillators, these scintillators have a basic scintillation mechanism that involves Föster energy transfer and self-absorption. They consist of one or two dopants [6]. The scintillation mechanism of organic scintillators is determined by the characteristics of the benzene ring. An organic scintillator scintillates despite its crystal form, whether it be it a liquid, a gas or imbedded in a polymer. The chemical bonds found within a benzene ring are: σ-bonds that are in the plane with bond angle 120° and are from sp^3 hybridization. The other chemical bonds found are π-orbitals which are out of plane and overlap. The π-electrons are completely delocalized.

detail not needed

Looking at the scintillation mechanism after the scintillator has absorbed the photon or excitation by ionization, the molecule will undergo vibrational relaxation to the S_{10} state. The S_{10} excited state radiatively decays to the vibrational sub-levels of the ground state. The lifetime of the S_{10} state is in the nanoseconds time range. The short lifetime allows for the fluorescence emission spectrum to be roughly a "mirror image" of the absorption spectrum, in other words, they have the same spacing. The emitted photons have less energy than the $S_{00} - S_{10}$ phase transition and that's where the important Stokes shift is observed. There is no $S_2 - S_0$ emission, thus there is an internal non-radiatively de-excitation occurring within the scintillator taking place in the picoseconds time range. The excited triplet state cannot decay to the ground state as a result angular momentum selection rules, it therefore results in a delayed fluorescence and phosphorescence [7].

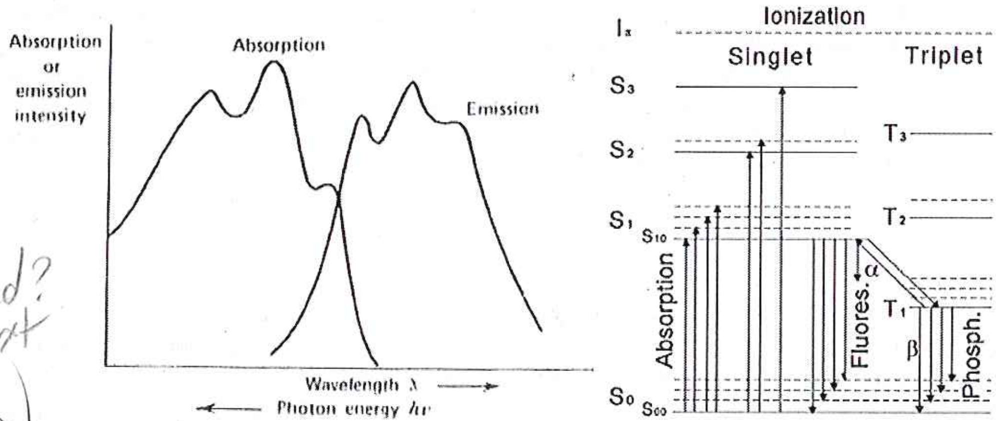

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Figure 1. A fluorescence absorption and emission spectra (left) and scintillation mechanism for and organic scintillator (right) [7].

3. Experimental Details

Four plastic scintillator grades were under study, three of which were obtained from ELJEN technologies and one from Dubna. 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 Kharkov type obtained from Dubna. The plastic scintillator grades under study are the EJ200, EJ208, EJ260 and the Kharhov type.

Several samples of each plastic scintillator grade were cut and polished at the Dzhelepov Laboratory of Nuclear Problems (DLNP) at JINR. Sixteen samples were cut to dimensions 20 mm by why?

how were these used?

20 mm, with 6 mm thickness. Additional samples of the ELJEN grade were polished to 10 mm thickness with dimensions 20 mm by 15 mm. Special sample holders were made to accommodate our samples due to their size. why?

16+ samples but only 4 data sets presented?

Channel 3 of the IBR-2 pulsed reactor at the Frank Laboratory of Neutron Physics (FLNP) in JINR was used to irradiate the samples [8]. The samples were subjected to irradiation with a beam of fast neutrons with energies above 1 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 the samples to different neutron fluxes to achieve various doses. The neutron flux density ranged between $1 \cdot 10^6 \sim 7.7 \cdot 10^6$. units?

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 Monte Carlo method is used to simulate statistical processes theoretically, in particular complex problems that cannot be solved/modelled using computer codes that use deterministic methods. The MCNP code is used to simulate neutron, photon and electron or coupled neutron/photon/electron transport. The code is in 3-D and is capable of tracking up to 34 particles and 4 light ions. The code takes into account the absorption and the moderation of the neutrons as they travel though matter. what did you do with it?

Table 1 below shows the neutron flux density, neutron fluences and doses at the various positions. How does this relate to T.1?

Table 1. Neutron flux density, neutron fluences and doses at the various positions.

schematic map of locations?

Sample position	Flux density (n/cm^2/s)	Fluence (n/cm^2)	Dose (Gy)
1	S.F $1 \cdot 10^6$	$1.2 \cdot 10^{12}$	66
2	$3.6 \cdot 10^6$	$3.6 \cdot 10^{12}$	199
3	$7.7 \cdot 10^6$	$9.4 \cdot 10^{12}$	510

u?

uncertainties? Source params?

Light spectroscopy was conducted using the Varian Carry 500 spectrophotometer 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 200-800nm. Transmission spectra were collected 8 weeks after irradiation, control samples were left un-irradiated in order to gauge the transmission loss. why?

why?

4. Light Transmission Results and Analysis

The light transmission spectroscopy results for each scintillator grade relative to the light transmission in air are shown below on the spectra on the left in Figures 2-5. In Figure 2, it is observed that at a wavelength of 400 nm the absorptive edge falls away completely for the EJ200 grade. The overall transmission of the grade decreases with an increase in dose but it is observed that at 755 nm, there is a slight increase in transmission at low doses. Figure 3 shows the light transmission spectrum of the EJ208 grade. It is observed from the spectrum that the absorptive edge falls away at 385 nm. At the highest exposed dose, there is an increase in transmission. At doses lower than 200 Grays, there is a decrease in light transmission. However we do observe an increase in light transmission for the lowest dose exposure at wavelengths above 705 nm. The transmission spectrum for the EJ260 is shown in Figure 4, it is observed that transmission starts to occur at wavelength 355 nm for a short wavelength range. The absorptive edge falls away completely at 460 nm. The overall transmission of the grade decreases with radiation damage. Figure 5 shows the transmission spectrum of the Kharkov type grade, the absorptive edge for this grade falls off completely at 400 nm. It is observed that the overall transmission of the grade increases with increasing dose. So?

what is this?

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. We consider the transmission loss of the highest dose exposure, 510 Grays. We observe a 3.4% transmission loss for the EJ200, 3% transmission increase for the EJ208 and 0% transmission loss for the EJ260 as the sample absorbs light in the wavelength range from 400 nm to 460 nm. The SF

not mentioned before... Ref?

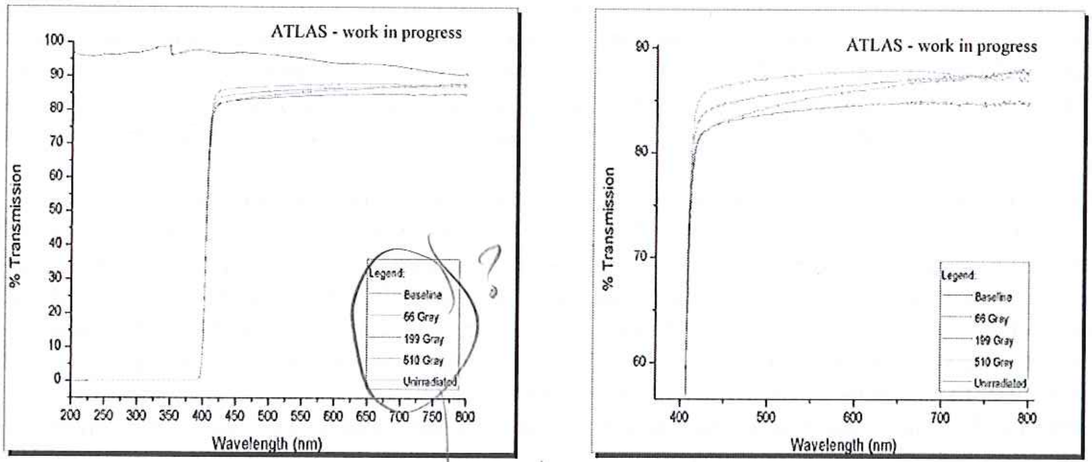
which dataset?

uncertainties?

So why pick 450nm?

Kharkov type grade shows a 2.9% transmission increase. The transmission loss is clearly shown in Figures 2-5 on the spectra on the right. no it's not

cannot differentiate if greyscale



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what does this mean?

Figure 2. Left: Transmission spectrum for un-irradiated and irradiated samples over several doses relative to air for the EJ200 grade. Right: Enlarged spectrum at wavelength 400 – 800 nm.

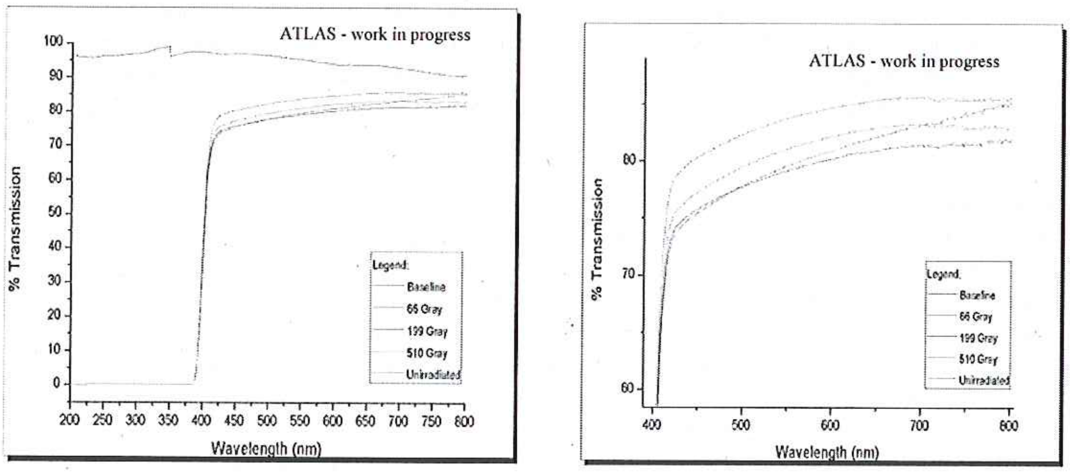

Figure 3. Left: Transmission spectrum for un-irradiated and irradiated samples over several doses relative to air for the EJ208 grade. Right: Enlarged spectrum at wavelength 400 – 800 nm.

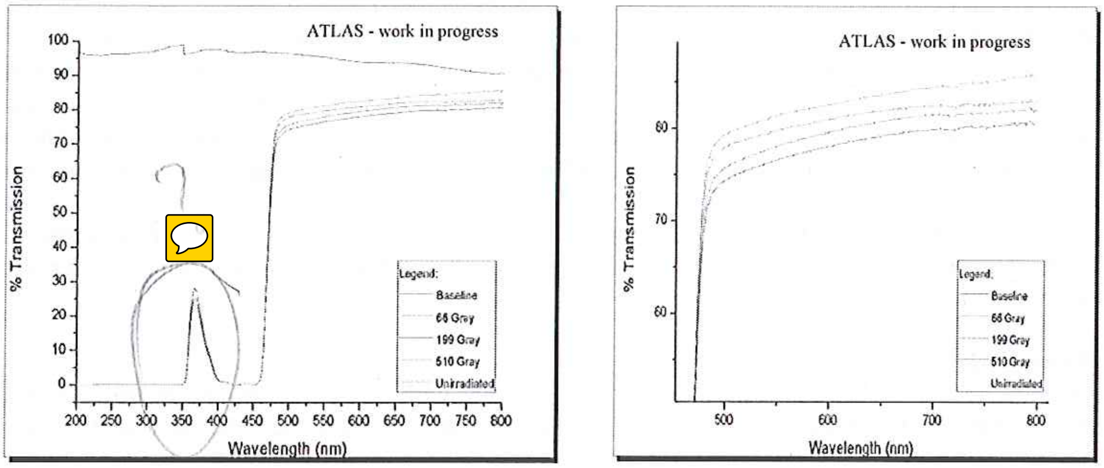

Figure 4. Left: Transmission spectrum for un-irradiated and irradiated samples over several doses relative to air for the EJ260 grade. Right: Enlarged spectrum at wavelength 460 – 800 nm.

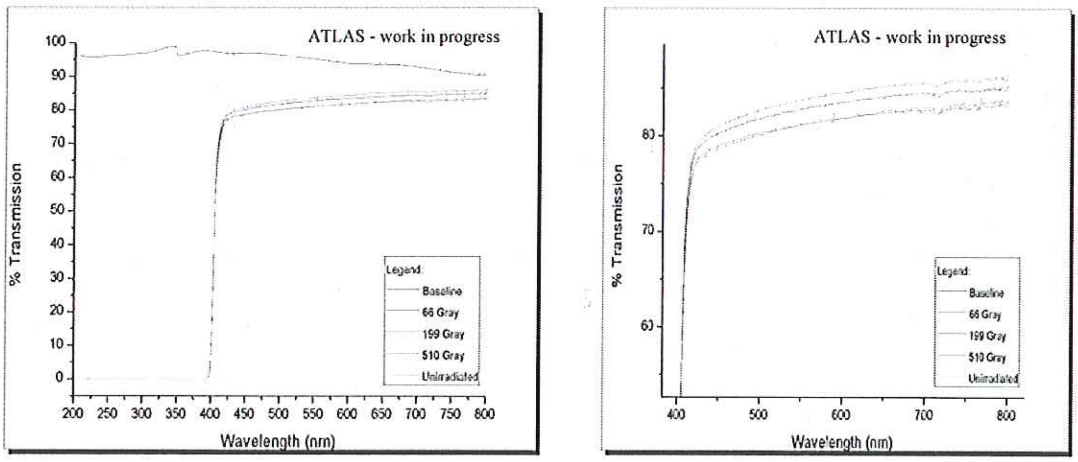

Figure 5. Left: Transmission spectrum for un-irradiated and irradiated samples over several doses relative to air for the Kharkov type grade. Right: Enlarged spectrum at wavelength 400 – 800 nm.

5. Conclusion

From the results obtained in this study, we observed that neutron irradiation has an effect on the light transmittance of plastic scintillators. We considered the transmission loss at wavelength of approximately 450 nm which corresponds to the peak absorption wavelength of the wavelength shifting optical fibres coupled with these scintillators within the Tile Calorimeter. The EJ200 showed the highest transmission loss with a 3.8% loss whilst the EJ260 showed no loss at all at wavelength 450 nm since it is observed that no transmission occurs in the wavelength range of 400 – 460 nm. Unlike the EJ200 and EJ260, the EJ206 and the Kharkov type had an increase in transmittance by 3% and 2.9% respectively.

WHY (?) what physics?

The overall transmission for the EJ200 and EJ260 decreases with exposure to radiation but there is no clear relationship between the dose exposure and the light transmittance from the three doses under study. The EJ208 and the Kharkov type both show an increase and decrease in light transmission. The highest dose exposure show an increase in light transmission whilst doses below 200 Grays show that there is a transmission loss for the EJ208. The Kharkov grade shows transmission loss for the lowest dose, below 100 Grays and an increase in transmission for doses above 200 Grays. No additional features were observed on the spectra due to radiation damage for all the grades compared to those observed in the proton irradiated samples [1].

All the results in this study are preliminary, they will be used as a guide in future studies. No conclusions can be made in this study on which plastic scintillator grade performed better under neutron radiation.

6. Upcoming work

Light yield tests will be done next. Raman spectroscopy will also be performed to observe if any structural damage occurred from the radiation damage. More samples will be irradiated at higher exposure doses to study on how the plastic scintillators behave higher doses of radiation damage. A study on the thickness dependence of the plastic scintillators will also be conducted. This will focus on studying the relationship between the thickness and the transmittance of the sample after undergoing radiation damage.

Acknowledgements

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References

[1] Jivan H, Erasmus R, Mellado B, Peters G, Sekonya K, Sideras-Haddad E 2014 *Radiation hardness of plastic scintillators for the Tile Calorimeter of the ATLAS detector* (Submitted to the SAIP conference) ?

[2] Succurro A 2012 *Physcis Procedia* **37** 229-237 title?

[3] Jivan H, Mellado B, Sideras-Haddad E, Erasmus R, Liao S, Madhuku M, Peters G, Solvyanov O 2015 *Journal of Physics conference series* **623** title?

[4] Pelwan C, Jivan H, Joubert D, Keartland J, Liao S, Peters G, Sideras-Haddad E 2015 *Journal of Physics conference series* **10** 645:012023 title?

[5] Liao S, Erasmus R, Jivan H, Pelwan C, Peters G, Sideras-Haddad E 2015 *Journal of Physics conference series* **10** 645:012021 " "

[6] D'Ambrosio C, Gys T *A short overview of organic scintillators* [Online] Available: http://ph-dep-dt2.web.cern.ch/ph-dep-dt2/CAT2005_3a.pdf → best source?

[7] Chen M 2011 Radiation detectors II: Scintillation detectors [Online] Available: www.physics.queensu.ca/~phys352/ " "

[8] Bulavin M. et al *Irradiation facility at the IBR-2 reactor for investigation of material radiation hardness* NIM B343 p26. Date?

[9] Monte Carlo Group: Los Alamos National Laboratory [Online] Available: https://mcnp.lanl.gov/

↑ not the right ref for MCNP5.