Characterization of plastic scintillators using magnetic resonance techniques for the upgrade of the Tile Calorimeter in the ATLAS detector

Chad Pelwan

University of Witwatersrand, *School of Physics*, P242

E-mail: chad.pelwan@gmail.com

Abstract. In this study we look at radiation damage and its adverse effects on plastic scintillators housed within the Tile Calorimeter (TileCal) of the ATLAS detector. The study focuses on determining how the interaction of ionizing radiation with plastic scintillators effects their efficacy and desired properties such as high light output and fast decay time. Plastic scintillators form an integral part of the ATLAS trigger system and their optimal functionality is paramount to the success of ATLAS. With the center of mass energy set to increase to $\sqrt{s} = 13$ TeV in 2015, the plastic scintillators are bound to experience an increase in structural damage due to increased beam energy. Magnetic resonance techniques provide insight into structural defects caused by ionizing radiation and, in particular, electron paramagnetic resonance (EPR) and nuclear magnetic resonance (NMR) will be employed in this study to qualitatively characterise this damage. In order to validate these results further a computational approach will look to replicate results seen using density functional theory (DFT) methods. Preliminary EPR results investigating four different types of plastic scintillators including three polyvinyl-toluene based Eljen technoligies: EJ200, EJ208 and EJ260, and one polystyrene based Dubna sample show that the Dubna sample, identical on the current scintillator used in the ATLAS detector undergoes structural damage when compared to the other Eljen samples. Correlating these results to light yield and light absorption experiments it can be shown that Eljen samples, the more favoured platics, undergo similar structural damage.

Introduction

After the first run of the Large Hadron Collider (LHC) in 2012, an overall upgrade of the 27 kilometre circumference particle accelerator was deployed [1]. Various components of the accelerator and its four large detectors were to be upgraded. A Toroidal LHC Apparatus (ATLAS) detector, a general purpose detector, is set to run at $\sqrt{s} = 13$ TeV after this phase two upgrade. With the LHC set to start up again in April 2015, the various components of the LHC that contribute the overall experiment should be able to withstand the increase in energy.

The minimum bias trigger scintillator (MBTS) plastics are situated around the beam pipe and have a pseudo-rapidity, η of $2.07 \leq |\eta| \leq 3.84$ [2]. There are 16 on each side of the ATLAS detector and they are 2 centimetres thick and are made of polystyrene based plastic. Their main purpose was to veto background from the beam before the nominal run of the detector and, since an effective mean was needed for proton-proton collisions, they provided a vital role in providing this. The MBTS plastics are identical to those in the Tile Calorimeter (TileCal) as

they are of the same make with 2 % dopants but differ in operation. Both the TileCal scintillator and MBTS plastics produce light when they are struck by energetic particles and the light they produce is passed down to photo-multiplier tubes (PMTs) via shifting fibres where they are converted into a digital signal and analysed. However, these plastics are susceptible to radiation damage induced by the diffractive particles that interact with them and it has been found that this interaction causes bonds to break in the benzene ring which is found in the molecule and is responsible for the scintillation mechanism in the plastics [3, 4].

Sample Preparation

Replicating the harsh environment the scintillators experience within the ATLAS detector is a non-trivial task. Two types scintillators were considered for this study: one polyvinyl-toluene based sample with three candidates of Eljen technology and one polyester based sample. The three Eljen samples were dubbed EJ200, EJ208 and EJ260, and the Dubna sample kept its name. The Dubna sample is identical to the MBTS plastic used in the ATLAS detector. Each of these samples were doped with their respective dopants that would aid the scintillation mechanism.

Since, in the detector, the plastics mostly experience ionization from the energetic particles, there was a need to replicate this interaction. The tandem accelerator at iThemba Labs, Gauteng provided a 6 MeV proton beam; each proton would need to pass through the scintillator and ionize the material. In order to do to, the particle interaction with the material was modelled using SRIM (Stopping and Range of Ions in Matter) which predicted that the stopping range in the two types of scintillators which occurred around 470 μm. TRIM (Transport of Ions in Matter) was used to calculated the average energy of each impinging proton at around 2.07 MeV. This value was needed to calculate the total absorbed dose the scintillator experiences by the protons. Before this could be done, each sample needed to be machined to a size that would fit onto a carousel placed into the tandem accelerator and a width less than the stopping range. A volume of $500\mu m \times 500\mu m \times 250\mu m$ was chosen and each sample was cut and polished to match this volume. Each sample as irradiated to two doses: 0.164 MGy and 1.46 MGy where the absorbed dose was calculated using

$$D = \frac{I_b \; A \; E_{ave} \; \Delta t}{q \; m_{ir}}, \tag{1}$$

where I_b is the beam current, A is the area of the irradiated spot, E_{ave} is the average energy per proton, Δt is the time spent irradiating the sample, q is the charge of the proton, and m_{ir} is the mass of the irradiated spot. After each sample has been irradiated they (and the un-irradiated samples) can undergo further testing.

Magnetic Resonance

Electron Paramagnetic Resonance

Electron paramagnetic resonance (EPR) is a spectroscopy technique that is used to study free electrons or ions that exist in a system by applying a large, homogeneous magnetic field to the system and supplying electromagnetic radiation whose frequency corresponds to that of a resonance frequency of the free electron or ion [5]. The electromagnetic radiation lifts the degeneracy of the energy states which can be measured. The assumption is that as the ionizing radiation imparts energy to the scintillators, the formation of free electrons and ions will be detected using this method. Experiments performed at the University of Witwatersrand have verified this assumption as a signal from both un-irradiated and irradiated samples were seen.

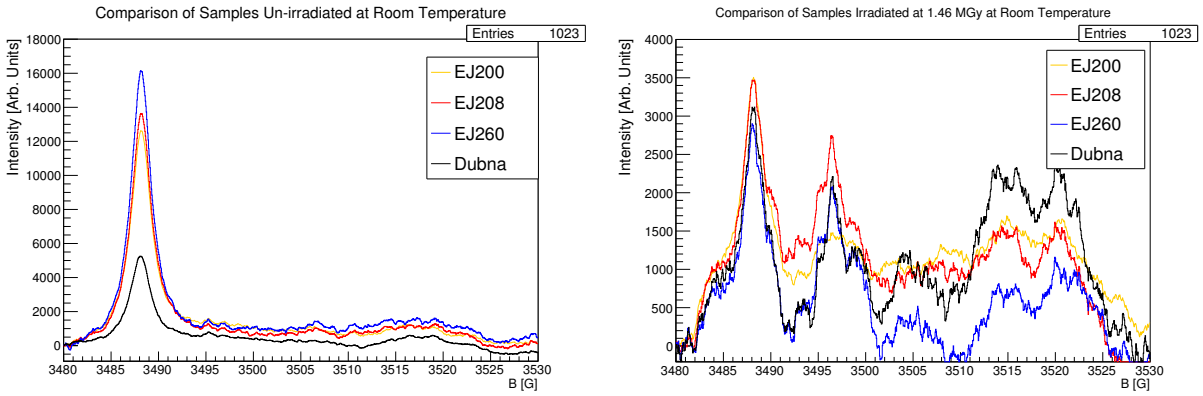

Figure 1. Comparison of all samples un-irradiated dose (left) and irradiated at a dose of 1.46 MGy (right)

Un-irradiated samples seen on the left of Figure 1 show that free electrons and ions exist in the sample before irradiation. Peak intensity are in arbitrary units since sample size plays an important role in EPR measurements. However, no mass re-normalization was needed since all the samples were cut to the same volume. On the right we see that secondary peaks begin to form as samples are irradiated. The interaction with the ionizing radiation causes a formation of other free electrons and ions ultimately damaging the scintillation mechanism as it alters the structure of the scintillator.

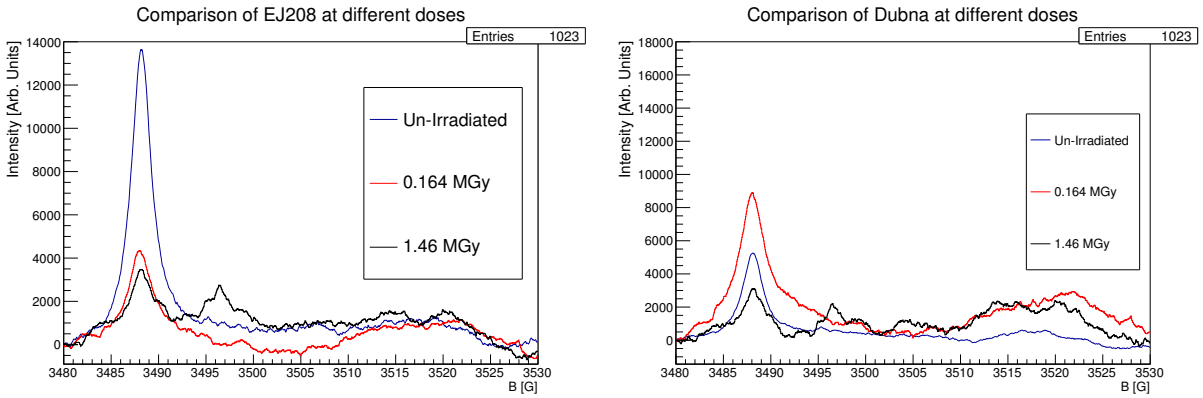

Figure 2. Comparison polyvinyl-toluene sample EJ208 (left) and polystyrene sample Dubna (right) at various doses

Figure 2 gives an indication of how the structure of the polyvinyl-toluene sample and polystyrene changes as they are irradiated at different doses. It is evident that, initially, there is a larger intensity of free electrons in EJ208 (left in Figure 2). As the samples are bombarded by protons this intensity decreases. This is hypothesised to be due to the fact that hydrogen forms. Ions are also formed when the energetic protons break bonds in the benzene base or break bonds between the functional group and the benzene base.

Nuclear Magnetic Resonance
Nuclear magnetic resonance (NMR) is analogous to EPR in that information about the electronic structure of the system can gathered when a sample in placed in a homogeneous magnetic field and the energy spin state degeneracy is lifted when eletormagnetic radiation is applied. The difference is that this is no longer the spin of the electron being probed, but that of a proton or ^1H [6]. The information obtained from these experiments would tell us about the Lamour frequency of ^1H which relates to the chemical shift in the material. The nearest electronegative atoms or functional groups effects the chemical shift of ^1H. The electronegative atoms and functional groups can be identified this way which will be paramount when we look to identify the ions formed from the irradiated samples.

This work will be conducted at the University of Witwatersrand in the Nuclear Magnetic Resonance Lab and will be coupled to the EPR experiments which will be refined and redone.

Computation Replication of Results
Since both EPR and NMR experiments are characterization techniques, they give a qualitative view of the scintillators and how damage effects them. A quantitative approach is needed in order to fully understand the problem. Thus, we look to model the system using a computational ab-initio approach. This will be done using density function theory (DFT) which is a theory for a correlated many-body systems that views any property of the system as a functional ground state energy, $E_0(\vec{r})$ [7]. From the ground state functional properties about the electronic structure of the system can be derived.

By isolating the optically active molecule (the benzene ring and its functional groups responsible for the scintillation mechanism) for both polyvinyl-toluene and polystyrene, we can use DFT methods to replicate both the EPR and NMR results[8]. The goal would then be to correlate the two spectra sets with properties from the DFT predictions. These include, but are not limited to, number of free electrons and ions in the system, ground and excited states of the system,and identification of functional groups and ions in un-irradiated and irradiated samples.

Conclusion
With the phase two upgrade of the ATLAS detector in mind, this project, accompanied with various other studies done on the plastic scintillators looks to eventually find a suitable candidate for the replacement of the MBTS platics as well as the the plastic scintillators housed inside the TileCal once they have lost their efficacy. We would also have a deeper understanding of radiation damage in plastic scintillators as a whole and hopefully this knowledge would aid in the design and manufacture of a plastic scintillator that is less susceptible to radiation damage than the technology currently available.

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