A study of radiation damage in plastic scintillators using magnetic resonance techniques for the upgrade of the ATLAS detector

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Abstract. During the phase two upgrade of the Large Hadron Collider (LHC), various components of the accelerator and ATLAS detector are due to be replaced or upgraded to withstand the increase in instantaneous luminosity. The minimum bias trigger scintillator (MBTS) plastics, located at $2.09 \leq |\eta| \leq 3.84$, on the EndCaps of the Tile Calorimeter (TileCal) in the ATLAS detector were subjected to ionizing radiation that allows them to track the trajectories and measure the energies of energetic particles. However, it is this interaction that causes structural damage within the polystyrene based MBTS plastics. The 6 MeV proton tandem accelerator at iThemba LABS, Gauteng is used to simulate the damage that the MBTS plastics are subjected to in the ATLAS detector in order to find a plastic scintillator type that could replace the one currently used. In order to understand structural damage, electron paramagnetic resonance (EPR) is employed to detect structural defects in two grades of polystyrene based plastic scintillators and three grades of polyvinyl based plastic scintillators. A replication of the spectra seen by the EPR technique will be attempted using a computational ab-intio approach. This should offer insight into the electronic structure of the plastic scintillators and how ionizing radiation causes structural damage to them. In this paper we present results from two Polyvinyl toluene (PVT) based plastic scintillators.

1. Introduction

With the second run of the Large Hadron Collider (LHC) set to begin in July this year, the shut down after the first run called for various components of the two ring, particle accelerator and its four detectors to be upgraded or replaced [1]. The minimum bias trigger scintillator (MBTS) plastics are an example of components that were to be replaced once their efficacy was depleted due to the exposure to energetic particles they interact with [2].

In total, there are 16 MBTS plastics situated around the beam pipe within the largest of the four detectors, the ATLAS detector, at a pseudo-rapidity between $2.07 \leq |\eta| \leq 3.42$ on the EndCaps of the Tile Calorimeter (TileCal) in the ATLAS detector. Before nominal operation of the LHC, the polystyrene based, 2 cm by 2 cm plastic scintillators were essential in vetoing background and finding an effective mean for the proton-proton collisions. When the MBTS plastics interact with energetic particles, usually ionizing radiation, there is an exchange of energy from the particles to the plastics scintillators. The plastic scintillators produce light, through the scintillation mechanism, which is then passed down via wavelength shifting fibres to

photo-multiplier tubes (PMTs) and the signal is digitized and can be analysed. However, this energetic interaction causes damage to the benzene molecule in the plastic scintillator and, in turn, the scintillation mechanism which is responsible for luminescence [3].

Understanding the damaged caused by ionizing radiation in plastic scintillators is non-trivial because of the amorphous nature of the materials, however, it is vital since the MBTS plastics are mainly subjected to low to medium energies (in the GeV range) in the ATLAS detector. Therefore, the study focuses on the interaction of particles with the plastics at relatively lower energies (in the MeV region) first hypothesising that it is possible to characterize damage in the plastic scintillators and, more specifically, to the benzene molecule. Damage has been induced to a plastic scintillator identical to that used for the MBTS plastic along with five other plastic scintillator grades. Two plastic scintillators will be investigated: polyvinyl toluene and polyester over a range of six doses. The two polystyrene samples are of a Dubna and Protvino make and the three polyvinyl toluene samples where called EJ200, EJ208, and EJ260. Electron paramagnetic resonance (EPR) be employed to characterize the damage seen in the various plastic scintillators and a computational ab-intio method will be used in an attempt to recreate the spectra [4]. In this paper we present preliminary results from EJ208 and EJ60, the two PVT based plastics. The calculation employs density functional theory (DFT) to build up the bulk material plastic from the benzene molecule. This should give us insight into which bonds are broken or formed when the particles interact with ionizing radiation [5].

2. Material Preparation and Irradiation

The damage to the plastic scintillators was induced by 6 MeV protons and SRIM (Stopping and Range of Ions in Matter) was used to model this interaction. Using SRIM, we found that the 6 MeV protons stopped at a distance of around 470 μm in the plastic scintillators. Therefore, the plastics needed to be cut and polished to a width thinner than that for ionization to occur. An extension of SRIM is TRIM (Transport of Ions in Matter), it was used to calculate the average energy of a proton, was approximately 2.07 MeV. This value added in calculating the dose each sample was subjected to. The samples were cut and polished to width of about 250 μ m with the volume that was around 1 cm $\times$ 1 cm $\times$ 250 μm. The samples were cut and polished in the Materials Preparation Room at the University of Witwatersrand.

Irradiation of samples took place at iThemba LABS, Gauteng using the tandem accelerator which is capable of accelerating protons to an energy of 6 MeVs. The beam is thenincident on the samples which are placed on a rotating carousel at the end of the beam line. In order to investigate the effect of radiation damage on the plastic scintillators, a range of doses were. Six doses were chosen, namely, 0.8 MGy, 2.5 MGy, 8.0 MGy, 25.0 MGy, 50.0 MGy, and 80.0 MGy. Each sample of each type of plastic scintillator was subjected to the different doses and analysed along with an un-irradiated sample. The exact dosage was calculated using the following equation

$$\mathcal{D} = \frac{I_B \; A \; E_{ave} \; \Delta t}{Q \; m_{Ir}}, \tag{1}$$

where I_B is the current of the beam incident on the sample with an irradiated are A for a time Δt. E_{ave} is the average energy calculated using the TRIM calculation and q is its charge (that of the proton). Once the samples are irradiated, they are then ready to be tested using the magnetic resonance spectroscopy techniques.

3. Electron Paramagnetic Resonance

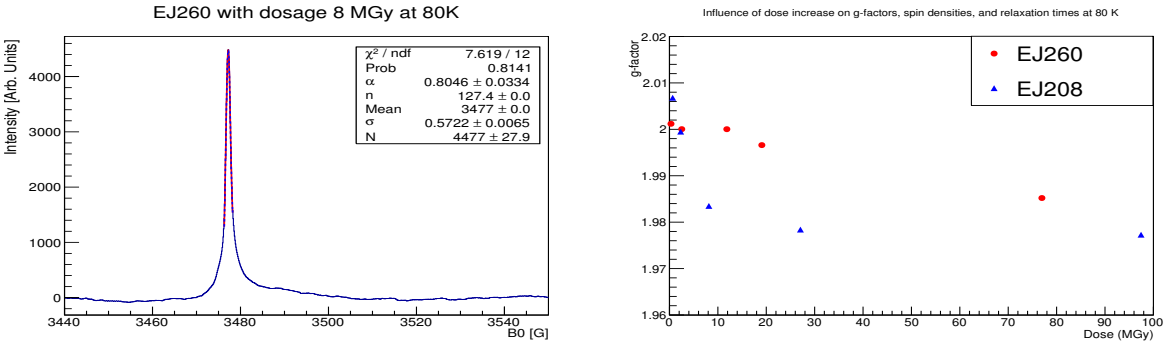
EPR is a spectroscopy technique that will be used to probe the electronic structure. The X-band, continuous wave (CW) ESP380 spectrometer was used to study how the increase in dosage effects the EPR spectrum produced for each sample. This is done by studying unpaired electrons and

ions in the samples when placed in a large magnetic field and a resonant frequency is applied. The following resonance condition summarizes this

$$\Delta E = h\omega_0 = g\mu_B B_0. \tag{2}$$

Equation (2) tells us that we can characterize a difference between two energy quantum states with a particular angular resonant frequency, ω_0. This is proportional to the magnetic field, B_0, the Bohr magneton, μ_B, and the g-factor of the sample, g. This should give us more insight into the environment in each sample and how it differs with an increase in dose. From the EPR spectra seen it is possible to obtain the g-factor of each sample, the relaxation time of the sample and the spin density. It is then possible to see how these parameters change with an increase of dose.

4. Preliminary EPR Results

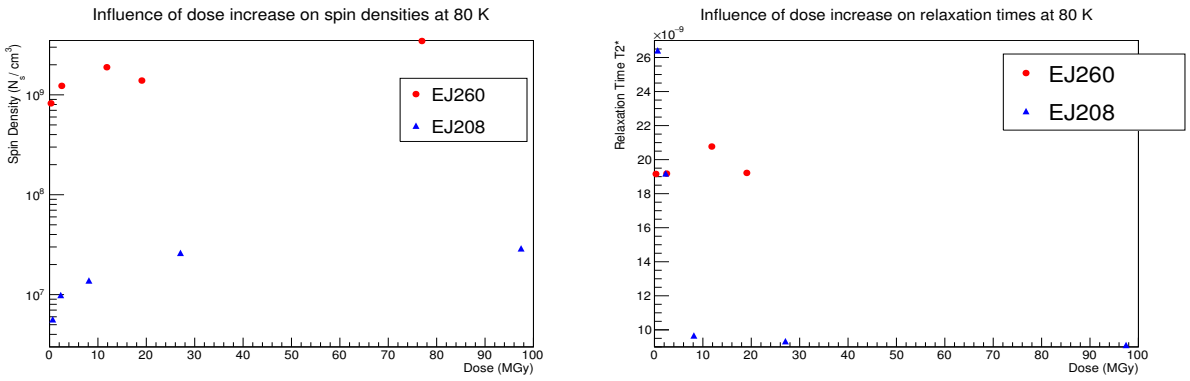


1 (a) 1 (b)

Figure 1: Integrated EPR spectra of irradiated EJ260 at 80 K (left) change in g-factor with dose for EJ260 and EJ208 (right)

Figure 1 (a) shows the spectra of EJ260 irradiated to a dose of 8 MGy. A CrystalBall distribution was used to fit the shape of the signal. This fit allows us to obtain information about various parameters like the g-factor seen in figure 1 (b). The asymmetric nature of the spectrum could arise from the anisotropy of the g-factor. The g-factor gives us an indication of the environment seen by the unpaired electrons in each sample. As the dose increases, we see that the g-factor decreases away from that of an un-irradiated reference sample. This could be due to the fact that defects in the samples caused by the ionizing radiation effect the potential the unpaired electrons see and thus change the g-factor.

Figure 2 (a) shows the unpaired spin concentrations, N_s, seen in both samples. This concentration is an indication of the number of unpaired electrons seen in a sample. N_s is obtained by integrating over the EPR absorption spectrum and dividing by the volume of the irradiated spot on the sample [6]. In general, the number of unpaired electrons increases as dosage increases. The increase is different for EJ260 than it is for EJ208. The reason for this is not yet know.



2 (a) 2 (b)

Figure 2: Influence of dose increase on unpaired spin concentration (left) and relaxation time T_2^* (right) at at 80 K

The relaxation time, T_2^*, is an indication of the spin-spin relaxation time for amorphous structures. It is calculated using full width at half the maximum of each integrated EPR peak.

$$T_2^* = \frac{2}{\sqrt{3}} \frac{\hbar}{g\mu_B B_{\mathrm{FWHM}}}. \tag{3}$$

It indicates the average time it takes for the spins to transition to a lower energy state. As the dose increases and more damage is induced, the relaxation time decreases for both samples.

5. Conclusion

The damage induced by ionizing radiation changes the structure in the plastic scintillators. It causes defects in the sample that shifts the g-factors in the samples and increase the number of unpaired electrons in them. This result is seen in both the experimental and computational work. The unpaired electrons also lose energy to other unpaired electrons and the defects in the material and there is a broadening in the EPR peak. This is due to the fact that the hyperfine parameters change when the samples are damaged by irradiation.

Future work will investigate radiation damage in one other PVT based plastic scintillator and three other polystyrene types.

6. References

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