Composite Scintillators - A new type of radiation hard scintillator

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Abstract. Composite scintillators are new promising detectors for use in severe radiation environments. They consist of crystal granules embedded into an optical transparent medium. This ensures a high radiation hardness within the scintillator with comparison to normal plastic scintillators. However, composite scintillators are low opacity materials as a result of the light scattered by the small crystal granules.

We report on optical and structural properties of these composite scintillators after irradiation using a neutron beam of above $1 \times 10^{14} n/cm^2$ generated by the IBR-2 reactor at the Frank Laboratory of Neutron Physics in Dubna, Russia. The irradiation effects were characterized using Raman spectroscopy, Light yield and Light Transmission measurements. We further report on the advantages and disadvantages of these composite scintillators; and problems that need to be addressed. Preliminary results indicate a small change in the light yield after neutron irradiation.

1. Introduction

The scintillation market already consists of many scintillation material such as liquid scintillators, scintillation plastics, crystals and ceramics. In high energy physics detectors, we require materials that will combine the advantages of scintillations crystals and the cost efficiency of plastic scintiallators into one material. The search for this materials has led to composite scintillators.

Composite scintillators are materials that consist of two or more components with a clear boundary between the matrix and the filler. They consists of an optical transparent medium with dispersed granules of scintillator. However, the challenge faced with this material is the fact that it is a low-transparent medium. This problem was solved by introducing an optical guide material over the scintillation layer. The composite scintillator material therefore consists of optical medium material made of either epoxy, poly-vinyltoulene and silicone. The light guide material is made of quartz glass and silicone or sapphire and molding silicone. The scintillation crystal is made of either silicates, garnets and diamond. This material will have applications in neutron detection, x-ray detection, gamma-ray detection and high energy physics detectors.

Multiple studies have been conducted to test the response of the different components of the materials under proton irradiation[1]-[4]. This study focuses on how the composite scintillators will behave under high neutron irradiation.

2. Theory

Neutrons are highly penetrating particles with zero charge and indirectly ionizing radiation. They can induce large radioactive doses through activation in the body of a material. Neutrons can be produced through various techniques with the most common being nuclear reactors, nuclear fission sources like DT-generators, accelerator-based sources which involve the spallation mechanism and radioactive decay of elements like Cf-252 [6]. Nuclear fission can either be a radioactive decay process or a nuclear reaction where a nucleus of an atom will split into smaller parts of lighter nuclei. Spallation is a process where fragments of a material are ejected from a body due to stress or impact. A spallation source produces pulsed or quasi-continuous neutron beams through the acceleration of protons hitting a target material of a heavy nuclei and releasing neutrons, where one spallation reaction can release up to 30 neutrons per incident proton particle [7]. Neutrons are widely used in the nuclear industry for material research, imaging and medical physics.

As compared to electrons, photos and heavy charged particles, neutrons undergo extremely weak electromagnetic interactions. Neutrons pass through matter largely impeded and only interact with the atomic nuclei. The nuclear reactions that occur between the neutrons and the atomic nuclei have a very low probability associated with them and hence Monte Carlo Techniques (MCNP) are used to perform neutron transport calculations. The probability for a reaction between two particles to occur can be measured through the cross section. The probability of a neutron between a neutron and an individual particle or nucleus is defined as the microscopic cross section whilst the probability of the interaction between neutron and bulk material is defined as macroscopic cross section[6].

When high energy neutrons interact with materials or materials are bombarded with neutrons, the material will degrade and be damaged through the process of collision cascades created within the material. The created collision in turn will produce point defects and dislocations within the material, these dislocations and defects are responsible for the microstructural changes that occur over time to materials that are exposed to radiation. The damage occurring in the material is a result of the interaction of an energetic particle with a lattice atom within a material. The collision causes a significantly large amount of kinetic energy transfer to the lattice atom from the neutron, the atom is then displaced from its lattice site and becomes what is known as a primary knock-on atom (PKA). As the PKAs collide with each other, they lose energy with each collision and terminate as interstitials; and effectively creating a series of Frenkel defects within the lattice. Another consequence of the collisions is heat, this is created from the electronic energy loss. The magnitude of the damage caused by a single 1 MeV of a neutron creating a PKA in an ion lattice is such that it will produce approximately 1100 Frenkel pairs. This is the cause of the damage within the material and the degrading of the material over time with exposure to radiation[8].

The IBR-2 reactor of the Frank Laboratory of Neutron Physics (FLNP) that belongs to the Joint Institute for Nuclear Research (JINR) in Dubna, Russia will be used to expose the materials to neutrons. A beam of neutrons will be extracted from the rector core, the core is of an irregular hexahedron shape that is composed of fuel element sub-assemblies. There is a three circuit and two loops cooling system where the first and the second circuits consist of liquid sodium coolants and the third is air. The IBR-2 produces one of the most intense pulse neutron

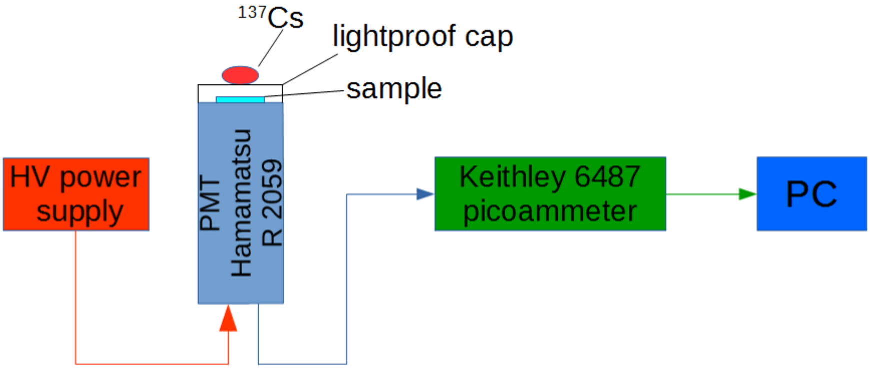

Figure 1. Schematic diagram of the pico-ammeter used for light yield measurements.

fluxes in the world at the moderator surface with a neutron flux of $\approx 10^{16} n/cm^2/s$ and a power of 1850 MW per pulse [9][10]. Fast neutrons in the energy range of $1 - 10 MeV$ were used in this study, fast neutrons create the most damage on materials due to the high energy. Fast neutrons were chosen specifically since these are the same energies found in high energy experiments like the ATLAS detector of the LHC [11] .

3. Experimental Procedure

The materials under study are the YSO:Ce crystals that consists of Slygard-184 optical silicone as a light guide and the YSO single crystal with YSO based granules, these crystals have dimensions $2cm \times 2cm$. The YSO single crystal scintillators with YSO based granules were irradiated with a beam of fast neutrons generated by the IBR-2 reactor core. Channel number three of the reactor was used for the study [9]. Three samples were irradiated with various neutron fluxes to measure the effect of neutron flux to the samples. The total flux exposed to the samples ranged between $3.8 \times 10^{12} n/cm^2$ and $1.8 \times 10^{14} n/cm^2$ and one sample was left un-irradiated for comparison measurements. Irradiation took place during the Autumn Run (17 October 2016 to 3 November 2016) of the IBR-2 reactor.

Light yield measurements were performed at the Dzhelepov Laboratory for Nuclear Problems (DLNP), the set up is illustrated in the figure above. The samples was placed above a photomultiplier tube (PMT) purchased from Hamamatsu. The PMT type used was the R2059 which is a head-on type PMT that has a bialkali photocathode material and a quartz window material. A lightproof cap covered the sample to avoid electromagnetic radiation. The signal detected by the PMT is measured using a pico-ammeter and recorded onto the PC system. THis setup is illustrated in Fig. 1. Measurements were performed in the absence of a radioactive source and thereafter, a cobalt-60 source was used to excite the samples. Measurements were performed soon after irradiation in November 2016, three more measurements were done thereafter with the last one performed in June 2017.

4. Results and Discussion

Sample 1 in the figures below represents the un-irradiated sample. Sample 2 represents the sample irradiated with $3.8 \times 10^{12} n/cm^2$, sample 3 represents the irradiated sample of $1.7 \times 10^{13} n/cm^2$ and sample 4 was exposed to the highest neutron flux of $1.8 \times 10^{14} n/cm^2$. Figure 2 shows the measurements done with residual current by testing the response of the composite scintillators when they are not excited by any radiation. We observe in Fig. 2 that the sample produces a

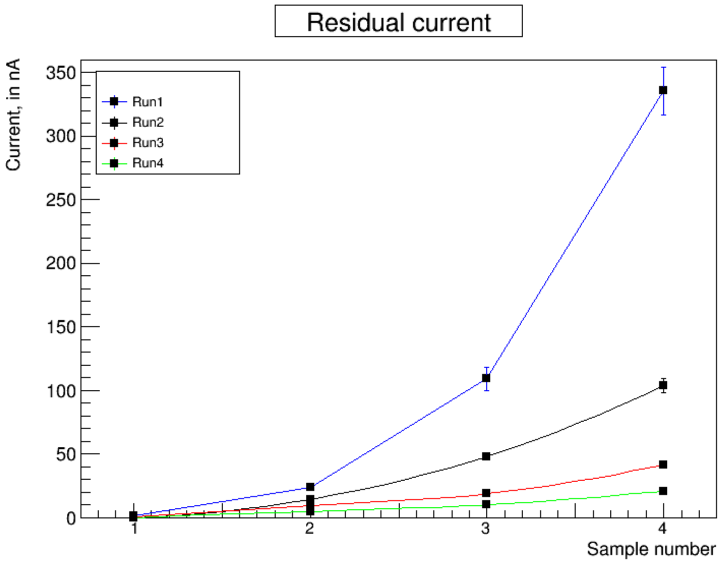

Figure 2. Residual current measurements for the composite scintillator.

greater current at samples irradiated with the higher neutron flux. We observe that the scintillators recover over time, especially sample number 4. Run 1, 2, 3 and 4 in Fig. 2 and 3 represent the different measurements done on the samples after irradiation. The first measurement referred to as Run 1 was performed immediately after irradiation in November 2016, the second in February 2017, the third in April 2017 and the last and forth run was performed in June 2017.

Figure 3 shows the response of the composite scintillators when they are exposed to a radioactive source, cobalt-60 that emits gamma radiation. The gamma rays emitted from the cobalt source excited the composite scintillators and luminescences as a result. From this figure, we observe that the sample does not show the same behaviour as in Fig. 2. As observed in the graph, the light yield of the composite scintillators is significantly lower with response to a source as compared to when no gamma radiation is exposed to the samples. From Fig. 3, there is no significant change between the irradiated and un-irradiated samples.

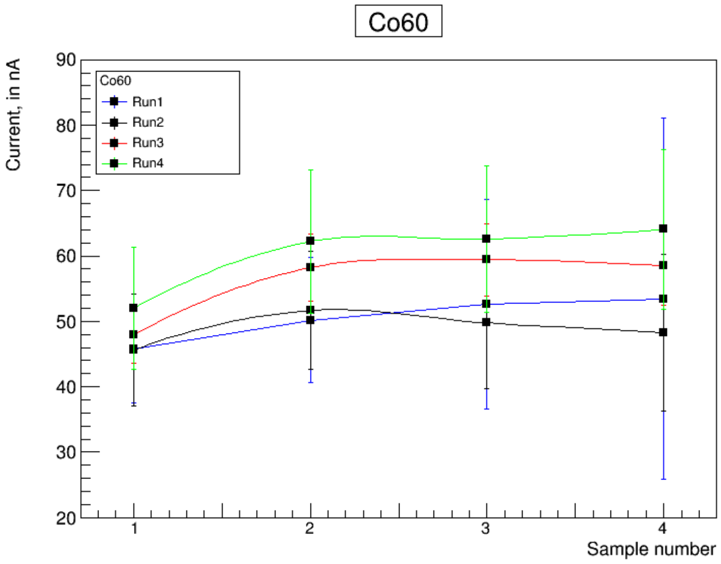

Figure 3. Co-60 current measurement for the composite scintillators.

5. Closing Remarks

From the results shown above, we observe how the composite scintillators are able to recover over time. The irradiated samples have a higher light yield as compared to that of un-irradiated sample when irradiated with gamma source (current due to induced activity is subtracted). We can conclude from the results shown in Fig. 2 and 3 that the composite scintillators do degrade under neutron radiation however further studies will need to be conducted with higher neutron fluxes since we only start to observe a significant change between the un-irradiated sample and sample number four that was exposed to a neutron flux of $1.8 \times 10^{14} n/cm^2$. The total neutron fluence the tile calorimeter of the ATLAS detector is exposed to in a year is $10^{12} n/cm^2$ [11], we are using this as a standard for the study and therefore we will need to go to higher neutron fluxes to study how the composite scintillators will be affected over time. Light transmission, Raman spectroscopy and photoluminescence measurements will be conducted to observe if the there is any change in other properties of the scintillators.

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References

[1] Ren-Yuan Zhu, 2015 *J. of Phys: Conference series* **587** 012055.
[2] Feygelman V M, Walker J K, Harmon J P, 1990 *Nucl. Instr. Meth. A* **290** 131.
[3] Feygelman V M, Walker J K, Harmon J P, 1990 *Nucl. Instr. Meth. A* **295** 94.
[4] Feygelman V M, Walker J K, Harmon J P, 1991 *Nucl. Instr. Meth. B* **53** 309.
[5] Holbert H E, Radiation effects and damage [Online] Available: *http://holbert.faculty.asu.edu/eee560/RadiationEffectsDamage.pdf/* [Accessed 24 06 2017]
[6] Hamilton D, Neutron Interactions with Matter [Online] Available: *https://pdfs.semanticscholar.org/presentation/2eb5/e6ac53e9e60e6a33c919e3e2a1fb3dbc3dae.pdf* [Accessed 04 10 2018]
[7] Bisanti P, 1986 *Magnetic properties of matter* (Turin:World Scientific) ed Borsa F, Tognetti V p 385-408

[8] Carpenter J M, 2004 *Neutron production, moderation and characterization of sources.*

[9] Bulavin M, 2015 Irradiation facility at the IBR-2 reactor for investigation of material radiation hardness *NIM* **B343** p26 - 29.

[10] FLNP, Frank Laboratory of Neutron Physics [Online] Available: *http://nph.jinr.ru/en/facilities/ibr-2* [Accessed 28 08 2018]

[11] Vasilescu A, 1997 Overview on the radiation environment in ATLAS and CMS SCT and the irradiation facilities used for damage tests. [Online] *preprint available as: ROSE/TN/97-3* Available: *http://cern.ch/rd48.*